

**THE DURABILITY OF TASMANIAN
BUILDING SANDSTONES**

by

C.E.Sharples B.Sc.(Hons)

Christopher

Edwin

Submitted in fulfilment of the requirements for the degree of
Master of Science.

Geology Department
UNIVERSITY OF TASMANIA
HOBART
1990

Except as stated herein, this thesis contains no material which has been accepted for the award of any other degree or diploma in any university, and, to the best of my knowledge and belief, this thesis contains no copy or paraphrase of material previously published or written by another person, except where due reference is made in the text.

A handwritten signature in black ink, appearing to read 'C. Sharples', written in a cursive style.

(signed) Chris Sharples

ACKNOWLEDGEMENTS

A large part of the work embodied in this thesis was carried out as work financed by two grants from the National Estate (Grant No.'s 3 [1982/83] and 10 [1984/85]), administered by Mr Leo Kelleher.

The National Estate work was supervised by Dr M.R.Banks (thesis supervisor), Dr D.C.Green and Mr I.Jennings (Mines Department), and Mr P. Spratt (England, Newton, Spratt & Murphy Pty. Ltd.), all of whom I wish to thank for their enthusiasm, guidance and assistance. The facilities of the Tasmanian Mines Department (including transport, work space and laboratory facilities), and those of the engineering firm England, Newton, Spratt & Murphy Pty. Ltd., were generously made available for the National Estate work.

Subsequent to the National Estate work, this project was continued on a part-time basis whilst I was engaged in related private consulting work. I am indebted to Mr John Dunn (Dunn Monumental Masons Pty.Ltd.), Mr Bruce James (Etna Stone Pty.Ltd.) and in particular to Mr Peter Rizzolo (Rizzolo Stone & Concrete Pty.Ltd.) for giving me permission to use data in this thesis which was obtained while consulting for them.

I have recieved assistance from numerous other individuals and organisations during the course of this work. I am indebted to all the other quarry operators approached who freely allowed me to sample their sandstone quarries, and to the Hydro-Electric Commission, through Mr Tom Bowling, for giving me access to a PUNDIT Ultra-sonic Pulse Velocity tester.

Discussions with Dr Alan Spry, Steven Forsyth, Ron Berry and Rick Donaldson were of great assistance in the development of parts of this work.

In addition, the following individuals have assisted, in one way or another, with the collection of some the data contained in this thesis: John Akerman (Dept. of Construction), Jon Knight (Tasmanian Development Authority), Meg Mitchell (Law Society of Tasmania) and Richard Morrison & Angela McGowan (Dept. Lands, Parks and Wildlife),.

CONTENTS

	Page No.
ABSTRACT	XII
CHAPTER ONE: INTRODUCTION	1
1.1 PROJECT PURPOSE AND AIMS	1
1.2 ORIGINS OF THIS PROJECT	2
1.3 PREVIOUS WORK	2
1.4 CONVENTIONS EMPLOYED	3
1.5 LIMITATIONS OF THIS THESIS	3
1.6 RATIONALE AND ORGANISATION OF THESIS	4
CHAPTER TWO: SANDSTONE	6
2.1 DEFINITION AND CLASSIFICATION OF SANDSTONES	6
2.2 SANDSTONE CONSTITUENTS	7
2.2.1 Quartz	7
2.2.2 Feldspar	7
2.2.3 Micas	7
2.2.4 Clays	7
2.2.5 Cements and stains	10
2.2.6 Other Minerals	11
2.3 TEXTURAL PROPERTIES	12
2.3.1 Grainsize	12
2.3.2 Sorting	12
2.3.3 Grain-shape and orientation (fabric)	12
2.3.4 Inter-granular texture	13
2.4 MACROSCOPIC PROPERTIES	15
2.4.1 Coherence	15
2.4.2 Colour	15
2.4.3 Bedding	16
2.4.4 Bedding Dip	17
2.4.5 Textural "defects"	17
2.4.6 Faulting, Jointing and fracturing	18
2.5 PHYSICAL PROPERTIES	19
2.5.1 Water Absorption and Effective Porosity	19
2.5.2 Bulk Rock Density	20
2.5.3 Compressive Strength	20
2.5.4 Surface Hardness	21
2.5.5 Tensile Strength - Point Load Strength Index	22
2.5.6 Flexural Strength and Modulus of Rupture	23
2.5.7 Ultrasonic Pulse Velocity	23
2.5.8 Abrasion Resistance	24
2.5.9 Dimensional Instability	24

CHAPTER THREE: TASMANIAN SANDSTONES	2 6
3.1 INTRODUCTION	2 6
3.2 LOWER PARMEENER SUPERGROUP SANDSTONES	2 6
3.2.1 The Lower Freshwater Sequence	2 8
3.3 UPPER PARMEENER SUPERGROUP SANDSTONES	3 1
3.3.1 Stratigraphy of the Upper Parmeener Supergroup	3 2
3.3.2 The Quartz Sandstone Sequence (Unit 2)	3 4
 CHAPTER FOUR: TASMANIAN BUILDING SANDSTONE SOURCES: SUMMARY OF DATA	 4 0
4.1 INTRODUCTION	4 0
4.2 MAJOR DISUSED QUARRIES	4 1
4.3 CURRENT QUARRIES	4 5
 CHAPTER FIVE: DECAY PROCESSES IN SANDSTONE BUILDINGS	 5 4
5.1 INTRODUCTION	5 4
5.2 SANDSTONE DECAY PROCESSES	5 4
5.3 MODES OF SANDSTONE DECAY IN BUILDINGS	5 5
5.3.1 Mechanical abrasion, impact, vibration, structural failure	5 5
5.3.2 Thermal stress failure	5 5
5.3.3 Alteration and solution of unstable minerals	5 6
5.3.4 Acid attack	5 6
5.3.5 Organic processes	5 7
5.3.6 Gypsum growth	5 7
5.3.7 Wet/dry cycling	5 7
5.3.8 Salt attack	5 9
5.3.9 Swelling clays	6 1
5.4 THE INFLUENCE OF STONE WORKING AND APPLICATION ON SUSCEPTIBILITY TO DECAY	6 7
5.4.1 Quarrying methods	6 7
5.4.2 Curing and working of dimensionally unstable sandstone	6 7
5.4.3 Stone finishing and laying methods	6 9
5.4.4 Building "micro-environments"	7 0
5.4.5 Building "macro-environments"	7 2

CHAPTER SIX: DURABILITY ASSESSMENT OF BUILDING SANDSTONES	73
6.1 INTRODUCTION	73
6.2 MEASUREMENT OF STONE PROPERTIES	73
6.2.1 The significance of particular properties in assessment of durability	74
6.3 ACCELERATED DECAY TESTING	79
6.3.1 Correlation of accelerated decay test results with sandstone properties and likely response to decay processes	80
6.4 ACTUAL STONE BEHAVIOUR IN BUILDINGS	87
6.4.1 Quantification of observed decay, and its relation to sandstone physical properties	88
6.5 CONCLUSIONS: OPTIMUM ASSESSMENT OF SANDSTONE DURABILITY	89
 CHAPTER SEVEN: GEOLOGICAL CONTROLS ON QUALITY AND DURABILITY-RELATED SANDSTONE PROPERTIES	 90
7.1 PURPOSE OF CHAPTER	90
7.2 PROPERTIES DETERMINING QUALITY AND DURABILITY OF SANDSTONES	91
7.3 SUITABILITY OF SITE	91
7.4 JOINT AND FRACTURE SPACING	93
7.4.1 Controls on joint and fracture spacing	93
7.4.2 Keys to location of widely jointed sandstones	100
7.5 BEDDING	103
7.5.1 Origin of bedform types	103
7.5.2 Controls on bedding thickness	108
7.5.3 Bedding dip	108
7.5.4 Keys to location of appropriately bedded building sandstones	108
7.6 COLOUR AND COLOUR PATTERNING	110
7.6.1 Iron minerals in sandstone	110
7.6.2 Origin of colouration; data used and its limitations	111
7.6.3 Origin of bulk colourations	112
(A) Grey/white bulk colourations	112
(B) Brown bulk colourations	113
(C) Geographic and stratigraphic patterns in bulk colouration	118
7.6.4 Origin of ferruginous staining patterns	120
(A) The origin of liesegang ring patterns	121
(B) Mechanisms of liesegang ring formation	126
(C) Evidence and tests to determine mechanisms of liesegang ring formation	127
(D) Other ferruginous stain patterns - patches, bands, nodules and surface "rinds"	133
7.6.5 "Bleaching" and "reduction spots" in ferruginous sandstone colouration	134
7.6.6 Keys to location of appropriately coloured building sandstones	135

7.7 TEXTURE AND TEXTURAL "DEFECTS"	136
7.7.1 Controls on textural characteristics	136
7.7.2 Keys to location of well-textured sandstone	138
7.8 MINERALOGY	139
7.8.1 Quartz	140
7.8.2 Feldspar	141
7.8.3 Clays	143
(A) Illite	145
(B) Kaolinite	148
(C) Halloysite	155
(D) Smectite and mixed layer illite/smectite	156
(E) Vermiculite	164
(F) Chlorite	167
Synthesis: Clays in the Quartz Sandstone Sequence	171
7.8.4 Ferruginous minerals (cements)	183
7.8.5 Other minerals	183
7.9 STRENGTH AND DIMENSIONAL STABILITY	184
7.9.1 Factors determining strength of sandstone	184
(A) Grainsize	185
(B) Sorting and homogeneity	185
(C) Grainshape and grain orientation	186
(D) Grain packing, interlocking and interpenetration	186
(E) Porosity	187
(F) Micro-fracturing	188
(G) Mineralogy	188
(H) Laminae	189
(I) Intergranular bonds: Introduction	190
(J) Intergranular bonds: quartz grain welding	190
(K) Intergranular bonds: authigenic quartz cement	192
(L) Intergranular bonds: ferruginous cement	196
(M) Intergranular bonds: clay	197
Summary of sandstone properties yielding high strength	199
7.9.2 Dimensional Instability	200
7.9.3 Keys to location of strong, dimensionally-stable sandstones	200
7.10 POROSITY AND DENSITY	203
7.10.1 Factors determining porosity and density of sandstone	203
(A) The sources of porosity in Tasmanian sandstones	203
(B) Controls on the development of porosity in Tasmanian sandstones	208
7.10.2 Keys to location of low porosity sandstones	210
7.11 THE WEATHERING OF NATURAL SANDSTONE OUTCROPS	212
7.11.1 Weathering alteration in the Elderslie sandstone quarry	212
7.11.2 Potential influences on sandstone outcrop weathering	217
7.11.3 Summary: The nature and significance of sandstone outcrop weathering	219
7.12 A PROPOSED SANDSTONE EXPLORATION STRATEGY	221
7.12.1 An exploration program to locate high quality yellow-brown sandstone in Tasmania.	221

CHAPTER EIGHT: CONCLUSIONS	227
8.1 INTRODUCTION	227
8.2 SUMMARY OF RESULTS	227
CHAPTER NINE: FURTHER WORK	231
9.1 INTRODUCTION	231
9.2 PROPOSED FUTURE WORK	231
9.3 A STANDARD DATA RECORDING FORMAT	235
REFERENCES	237

APPENDICES

APPENDIX ONE: SANDSTONE SOURCE DATA SHEETS	249
APPENDIX TWO: SPECIMEN CATALOGUE	290
APPENDIX THREE: SANDSTONE DATA COLLECTION AND TESTING METHODS	294
A 3.1 DETERMINATION OF MINERAL CONSTITUENTS	294
A 3.1.1 Clastic grains, mineral cements, clays	294
A 3.1.2 Clay Matrix (XRD)	296
A 3.1.3 Scanning Electron Microscopy (SEM)	300
A 3.2 DETERMINATION OF TEXTURAL PROPERTIES	301
A 3.2.1 Grainsize and sorting	301
A 3.2.2 Grainshape and orientation	303
A 3.2.3 Inter-granular texture	303
A 3.3 DETERMINATION OF MACROSCOPIC PROPERTIES	304
A 3.3.1 Coherence	304
A 3.3.2 Colour Determination	304
A 3.3.3 Bedding, Jointing, Textural Defects	304
A 3.4 DETERMINATION OF PHYSICAL PROPERTIES	306
A 3.4.1 Effective Porosity, Water Absorption and Bulk Density determination	306
A 3.4.2 Tensile Strength - Point Load Strength Index	307
A 3.4.3 Ultrasonic Pulse Velocity	309

VII

A 3.5 DURABILITY ASSESSMENT BY SALT CRYSTALLISATION TESTS	311
A 3.5.1 Sodium Sulphate Soundness Test (full immersion)	311
A 3.5.2 Sodium Chloride Salt Crystallisation Test	312
APPENDIX FOUR: CHECKLIST OF REQUIREMENTS FOR HIGH QUALITY AND DURABILITY BUILDING SANDSTONE	313
A 4.1 INTRODUCTION	313
A 4.2 CRITERIA FOR HIGH QUALITY AND DURABILITY SANDSTONE	313
A 4.3 STONE TESTING METHODS	317
APPENDIX FIVE: DATA RECORDING SHEETS	318
APPENDIX SIX: ULTRASONIC PULSE VELOCITY MEASUREMENT FOR RAPID FIELD ASSESSMENT OF BUILDING SANDSTONE QUALITY	326
APPENDIX SEVEN: THE DURABILITY OF SANDSTONES WHEN SUBJECTED TO THE CYCLIC SALT CRYSTALLISATION TEST	417
APPENDIX EIGHT: TASMANIAN EARLY TRIASSIC SANDSTONES: DATA COLLECTED DURING PRIVATE EXPLORATION WORK	432
APPENDIX NINE: TASMANIAN EARLY TRIASSIC SANDSTONES: DATA ABSTRACTED FROM APPENDIX ONE	435
APPENDIX TEN: QUARTZ SANDSTONE SEQUENCE: JOINT SPACINGS	437
APPENDIX ELEVEN: DISTRIBUTION OF CLAY TYPES, HALITE AND GYPSUM IN EARLY TRIASSIC SANDSTONES DRILLED NEAR BOTHWELL	439
APPENDIX TWELVE: SCANNING ELECTRON MICROSCOPY: CLAYS IN TASMANIAN BUILDING SANDSTONES	445

LIST OF FIGURES

<u>Figure No.</u>	<u>Page No.</u>	
2.1	Classification of sandstones	6
2.2	Representative structures of the major clay groups	9
3.1	Palaeogeography of Tasmania during deposition of the Lower Freshwater Sequence	28
3.2	Stratigraphy of the Permian Nunamara Sandstone Quarry	30
3.3	Distribution and palaeogeography of the Early Triassic Quartz Sandstone Sequence	34
4.1	Tasmania: Major sandstone quarries locality map	43
4.2	Hobart area: Major sandstone quarries locality map	44
6.1	Relationship between Ultrasonic Pulse Velocity and Strength/Porosity in Tasmanian building sandstones	77
6.2	Relationship between Durability (in the cyclic NaCl salt test) and Strength/Porosity for 34 Tasmanian building sandstone specimens	82
7.1	The importance of topography in choosing quarry sites	92
7.2	Predicted regional variation in Mesozoic and Tertiary fault and joint densities in the Tasmania Basin	94
7.3	Actual joint spacings measured in quarries and outcrop sites in the Quartz Sandstone Sequence	96
7.4	Relationship of flow regime to bedforms deposited	103
7.5	Ideal sequence of bedding types for meandering fluvial system sandstones	105
7.6	Geographical distribution of bulk colourations and clay types in Early Triassic sandstones, SE Tasmania	119
7.7	Comparison of degree of ferruginous stain patterning with distance from nearest known contacts with dolerite bodies; Early Triassic sandstones, Tasmania Basin	122
7.8	Patterns of liesegang ring distribution predicted by theories of (A) pattern formation contemporary with dolerite intrusion, and (B) late stage near-surface pattern formation	125

IX

7.9	Bothwell drillhole "Thorpe": distribution of clay types through the dominantly sandstone interval of the Early Triassic Quartz Sandstone Sequence	153
7.10	Geographic distribution of clay types in the Early Triassic Quartz Sandstone Sequence, Tasmania	162
7.11	Schematic representation of postulated origins and authigenesis of clays in the Early Triassic Quartz Sandstone Sequence, Tasmania	172
7.12	Mechanisms of sandstone clay content increase subsequent to deposition	176
7.13	Early Triassic Quartz Sandstone Sequence: Relationships between total clay content and dominance of specific clay types	177
7.14	The provenance of minerals deposited in the Early Triassic Tasmania Basin (Quartz Sandstone Sequence)	181
7.15	Correlation between strength and porosity in Tasmanian building sandstones	188
7.16	Relationship between dry bulk density and effective porosity in Permian and Triassic Tasmanian building sandstones	204
7.17	Relationship between total clay content and effective porosity for Permian and Triassic Tasmanian building sandstones	204
7.18	Relationship between smectite content and effective porosity in Permian and Triassic Tasmanian building sandstones. Smectite content presented as volume percentage of total clay	205
7.19	Relationship between smectite content and effective porosity in Permian and Triassic Tasmanian building sandstones. Smectite content presented as volume percentage of total sandstone mineral matter	205
7.20	Elderslie Quarry: surface outcrop weathering effects as indicated by mineralogical and textural variations	215
A 3.1	Visual comparator chart for estimation of sandstone grain sorting	302
A 3.2	Visual comparator chart for determination of roundness and sphericity in sandstone grains	303
A 3.3	Typical intergranular textures in sandstones	305
A 3.4	Measurement of Point Load Strength Index (tensile strength) parallel (a) and normal (b) to bedding	308

LIST OF PLATES

<u>Plate No.</u>		<u>Page No.</u>
2.1	Strong intergranular texture (Cobbs Hill Stone)	1 4
2.2	Weak intergranular texture (Elderslie Stone)	1 4
4.1	Pontville White sandstone (Source 22)	4 8
4.2	Pontville Brown sandstone (Source 21)	4 8
4.3	Nunamara sandstone (Source 25) in Old St. Mary's Hospital	4 9
4.4	Buckland Quarry white sandstone (Source 28)	4 9
4.5	Cobbs Hill Quarry sandstone (Source 23)	5 0
4.6	Oatlands Quarry sandstone (Source 24)	5 0
4.7	Elderslie Quarry sandstone (Source 26)	5 1
4.8	Linden Quarry sandstone (Source 27)	5 1
4.9	Buckland Quarry "striped" sandstone (Source 28)	5 2
4.10	Molesworth Quarry sandstone (Source 29)	5 2
4.11	Mike Howes Marsh Quarry (Source 30)	5 3
5.1	Decay resulting from gypsum growth around a mortar joint	5 8
5.2	Severe decay and discolouration due to rising damp and salt attack	5 8
5.3	Deep cracking in lithic sandstone, probably due to excessive smectite content	6 3
5.4	Severe exfoliation and rounding in smectite-rich sandstone	6 3
5.5	Cracking parallel to joints in high-smectite sandstone	6 5
5.6	Splitting beneath ledges due to water soaking into smectite-bearing sandstone	6 5
5.7	Crack which formed in freshly quarried dimensionally unstable sandstone within days of being cut, worked and dried	6 8
7.1	Closely spaced sub-parallel jointing within the Tertiary Derwent graben. Linden Quarry.	9 7
7.2	Massive bed overlying plane-laminated sandstone at Elderslie Quarry. Also shown are superficial pachydermal fractures	1 0 6

7.3	Cross-bedded sandstone, Elderslie Quarry	106
7.4	Uniformly brown vermiculite-rich sandstone, Melton Mowbray	117
7.5	Greenish-grey chloritic lithic sandstone, showing brown colouration close to the natural outcrop surface. Kempton.	117
7.6	Uniform grey-white sandstone, showing abrupt boundary with "lobe" of strong liesegang ring staining	124
7.7	Liesegang rings controlled by joint planes	131
7.8	Liesegang rings sub-parallel to natural outcrop surface in very widely jointed sandstone	131
7.9	Dark porous patches in Domain Quarry sandstone	138
7.10	Detrital feldspar grain in Early Triassic sandstone (S.E.M.)	142
7.11	Detrital feldspar grain, showing columnar surface texture (S.E.M.)	142
7.12	Authigenic illite flakes showing radiating growth habit (S.E.M.)	146
7.13	Authigenic illite flakes showing delicate lath-like projections (S.E.M.)	146
7.14	Authigenic kaolinite "books" and plates (S.E.M.)	149
7.15	Authigenic kaolinite aggregate (S.E.M.)	149
7.16	Detrital kaolinite clay pellet (S.E.M.)	151
7.17	Detail of detrital kaolinite clay pellet (S.E.M.)	151
7.18	Authigenic halloysite rods (S.E.M.)	155
7.19	Authigenic smectite growing on authigenic quartz (S.E.M.)	157
7.20	Authigenic mixed layer illite/smectite (S.E.M.)	157
7.21	Authigenic chlorite growing on authigenic quartz (S.E.M.)	168
7.22	Authigenic chlorite and authigenic smectite (S.E.M.)	168
7.23	Authigenic quartz cements and welded grain boundaries	191
7.24	Clay - pellets, interstitial, intergranular	191
7.25	Smectite-rich sandstone showing high proportion of clay	198
7.26	Ferruginous cement	198
7.27	Elderslie Quarry, upper cross-bedded face showing corner from which samples E1 - 11 were taken	213

ABSTRACT

Tasmanian building sandstones have been almost entirely quarried from fluvial sandstones of the Early Triassic Quartz Sandstone Sequence and the Permian Lower Freshwater Sequence. These continue to be the only horizons considered prospective for new sources of high quality building sandstone.

Technical data on all significant Tasmanian building sandstone sources is presented.

There are three methods of assessing and predicting sandstone quality and durability in the built environment:

- 1) Inferring predicted stone behaviour from measurement of sandstone properties.
- 2) Accelerated decay tests.
- 3) Observed performance in existing buildings.

Each method is subject to limitations. Optimum assessments are made by interpreting a combination of data from all three approaches, in the light of an understanding of the nature of sandstone properties and of the processes of sandstone decay.

Investigation of the geological processes controlling the genesis of sandstone properties has led to the development of models to facilitate exploration for high quality building sandstones:

Most jointing in Parmeener Supergroup sandstone is related to Mid-Mesozoic and Early Tertiary faulting. The areas most prospective for widely-jointed sandstones are predicted on the basis of known regional variations in fault densities.

The bulk colour of sandstone is related to the content of iron-rich minerals in the sandstone, particularly vermiculite, smectite and chlorite, which oxidise to yield brown ferruginous colouring. Liesegang rings form in proximity to iron-rich basic igneous rocks, probably through weathering-related groundwater processes.

For most building purposes, thick and massively-bedded sandstone is the ideal. There is no way of predicting the occurrence of such beds on a regional or local scale, except insofar as they are more prevalent in the stratigraphically lower parts of the Triassic Quartz Sandstone Sequence as a whole.

Sandstone strength and porosity are functions of mineralogy and intergranular texture. The geological controls on these properties are discussed. The occurrence of superficial pachydermal fractures on natural outcrops is considered to be an indicator of sandstones having weak intergranular textures resulting in a high degree of dimensional instability.

Smectite swelling clay is detrimental to sandstone durability. The proportion of smectite in sandstone varies markedly within individual outcrop areas, but on a larger scale there appear to be regional and possibly stratigraphic patterns in smectite occurrence. The smectite (together with vermiculite) is considered to have formed by alteration of volcanic dust deposited from ash clouds produced by contemporaneous volcanic sources to the southeast of the Tasmania Basin.

Weathering of natural outcrops alters important sandstone properties, most importantly through near-surface kaolinisation. An exploration program for high quality building sandstones is proposed which takes account of this limitation, and of the exploration models developed in this work.

The major contribution of this thesis is that an understanding has been achieved of the avenues of research which are necessary to further the development of models explaining the genesis of important quality and durability-related sandstone properties. These are listed.

CHAPTER ONE

INTRODUCTION

1.1 PROJECT PURPOSE AND AIMS

Tasmania has a wealth of historical sandstone buildings, a large proportion of which are registered on the National Estate. However, many of these buildings are in a poor state of repair, with decay of low durability sandstones used in their construction being a major cause. For some years the durability of sandstone has been a matter of concern to people working on the maintenance and restoration of such buildings. Durability is also of importance in choosing stone for the construction of new sandstone buildings.

Most information available to date on Tasmanian sandstones has had little direct relationship to stone durability when used for building purposes.

The ability to choose durable sandstones for use in buildings depends on understanding the processes involved in stone decay, and upon the ability to identify stones with the properties necessary to resist those decay processes.

Much work has previously been undertaken, in Tasmania and elsewhere, to study the processes of sandstone decay (eg, see Winkler 1973, Cripps & Spratt 1979, Spry 1981, Spratt 1982).

This project was not primarily aimed, therefore, at ascertaining why sandstones in Tasmanian buildings are decaying, since this is largely understood. Rather, the present work had the following aims:

1. To ascertain which tests or measured stone properties can most reliably indicate the durability of Tasmanian sandstones in the built environment.
2. To provide an inventory of the major historical and modern sources of building sandstone in Tasmania, incorporating data on stone properties influencing durability (as determined by sampling and testing).
3. To investigate the influence of depositional, diagenetic, tectonic and weathering environments in producing those sandstone properties which govern durability. The ultimate aim of such work is to produce models of the geological environments in which the most durable building sandstones might have formed. Such models could then facilitate future exploration for high quality sandstone.

In addition to consideration of sandstone durability, some consideration is also given to aesthetic variations in Tasmanian sandstones (colour, patterning, inhomogeneities). Such aesthetic factors may not affect stone durability, but are nonetheless important in determining the suitability of stone for particular types of building work.

The aim of this project has not been to find ways of prolonging the life of stone already in use in buildings, by stopping or slowing decay of poor sandstone. Rather, the emphasis is on enabling durable sandstone to be selected in the first place, so that fewer expensive restoration or protective works will need to be applied at a later date.

1.2 ORIGINS OF THIS PROJECT

This research project originated in studies by Peter Spratt (of England, Newton, Spratt & Murphy Pty. Ltd.) and Dr D.C. Green (Tasmanian Mines Department) of building sandstones used in the historic Port Arthur convict settlement (Cripps & Spratt 1979, Green & Woolley 1981, and Spratt 1982).

The National Estate supplied a grant commencing in 1983 to undertake a broader study on the durability of Tasmanian sandstones. The Tasmanian Mines Department (now known as the Department of Resources and Energy, Division of Mines) provided work space, transport and facilities for the project. The project was also accepted as a Masters project by the University of Tasmania, thereby making University facilities available.

An initial report (Sharples *et al.* 1984) on the work was prepared as an unpublished Mines Dept. report. The writer has subsequently continued to work in the field as an independent contractor, so that the present thesis includes the material in the 1984 report, updated and with new material added as a result of subsequent work. Some of the earlier data (eg, quantitative clay XRD results) has been recalculated in the light of better methods.

1.3 PREVIOUS WORK

A great deal of work has been performed outside Australia on building stone properties and durability in the human environment, particularly in Europe due to the great number of old stone buildings and monuments there (see in particular Winkler 1973 and Amoroso & Fassina 1983).

Much of the overseas work is not relevant to the Tasmanian situation, since it deals with environmental stresses (eg, pollution) which are not pronounced in Tasmania, and also very often deals with sandstones of different character from Tasmanian stone (eg, overseas building sandstones may have more carbonate cement, and less smectite clay, than Tasmanian sandstones).

Early work on building stones in Australia was based on incomplete understanding of the processes of sandstone decay, and did not provide much useful quantitative data. Perhaps the classic early work was the beautifully illustrated "Building and Ornamental Stones of Australia" (Baker 1915).

In recent times a considerable amount of work has been undertaken in the field of sandstone durability. Dr Alan Spry's 1983 report is the most recent comprehensive collection of data on building sandstones throughout Australia.

In Tasmania sporadic work has been done in the past, involving determination of well known parameters such as compressive strength, bulk density, petrography and salt crystallisation test soundness of sandstones (eg, Threader 1969, 1982).

In the late 1970's, serious efforts were instigated, primarily by Peter Spratt, to study systematically the durability of Tasmanian sandstones. Work on the Port Arthur penal settlement resulted in the recognition of the importance of the swelling clay smectite (montmorillonite), and of wet-dry environmental cycles (Cripps & Spratt 1979, Spry & Spencer 1979, Green & Woolley 1981, and Spratt 1982).

The present project was initiated as a direct result of the Port Arthur work.

1.4 CONVENTIONS EMPLOYED

Map grid references employed in this thesis refer to the Universal Transverse Mercator Grid Reference System used on modern Tasmanian topographic maps (Australian Map Grid Zone 55G). Co-ordinates given consist of the 100,000 metre square identification letters, followed by eastings, then northings.

Specimens are generally referred to by original field numbers in the body of this thesis; equivalent Geology Department (University of Tasmania) and Division of Mines (old name: Department of Mines) specimen numbers for collections housed in those two repositories are listed in Appendix Two. Outcrop sites and specimens examined and tested during work for Rizzolo Stone & Concrete Pty. Ltd. and the Tasmanian Development Authority are given field numbers according to a system developed concurrently with the later phases of work on this thesis (see Sharples 1990).

1.5 LIMITATIONS OF THIS THESIS

This thesis was prepared over a number of years, during which time the writer was concurrently working in the field of building stone research as an independent contractor.

A large proportion of the data on sandstone sources (Appendix One) was collected during the early part of this project. Later, during the period 1987 - 89, additional laboratory testing criteria were used in the assessment of sandstone quality. These criteria include determination of quartz and iron oxide cement percentages (as well as clay), quantitative determination of intergranular texture, use of the sodium sulphate crystallisation test, and determination of stone colour and strength in both the wet and dry state. All these criteria are discussed in this thesis (Chapter Two and Appendix Three), and are considered to be very important.

In addition, experience with numerous fresh and weathered outcrops has indicated that naturally weathered sandstone outcrops commonly become significantly weakened and more porous (largely due to authigenic clay growth) to a depth of a metre or more below the outcrop surface. This weathering effect appears to become significant after only a few decades exposure, so that samples taken from old buildings may be similarly affected. Investigations of these weathering processes are still in progress.

The writer now considers it a waste of time conducting most laboratory tests on weathered outcrop samples; fresh sub-surface samples are essential (although mineralogical analysis - microscopy and XRD - is still useful on surface samples, because while clay and quartz proportions may change, the presence of detrimental minerals such as smectite clay can generally still be determined).

As a result of the above considerations, much of the data originally collected for this thesis is limited, in that the range of tests conducted is less than is now considered fully adequate, and furthermore many of the samples originally collected from older, disused sources are weathered samples from old excavations and buildings.

Time has not allowed a comprehensive re-sampling and re-testing of all the quarry sources investigated in this thesis. However, this does not mean that the data in this thesis is now valueless - it is simply limited. In order to assess the reliability of the data as an indication of fresh stone quality, Appendix One includes an indication of the freshness of each sample tested.

Despite the limitations on the actual data obtained for this thesis, the work has substantially contributed towards a primary aim of this thesis, that of ascertaining the best testing procedures for sandstone evaluation. The information on testing criteria and methods contained herein will now allow better assessments of sandstone quality to be carried out than was possible at the outset of the project.

1.6 RATIONALE AND ORGANISATION OF THESIS

The information presented in this thesis comprises not only the results of original work by the author, but also a synthesis of previous work by other researchers. The intention is to provide a reasonably comprehensive compilation of information relevant to studies of the quality and durability of Tasmanian building sandstones. It is hoped that the presentation of such a body of information will encourage the adoption of a more standardised approach to building sandstone exploration and durability assessment than has previously been the case in Tasmania.

The specific research aims of this thesis are laid out in Section (1.1). The manner in which this thesis is organised to achieve those aims can be outlined as follows:

Aim 1:

To ascertain which tests or measured stone properties can most reliably indicate the durability of Tasmanian sandstones in the built environment.

This is an aim which continues to be a matter for research and debate in the stone industry, and the present work by no means produces final answers. To the extent to which this aim is tackled in this thesis, the approach is as follows:

CHAPTER TWO: SANDSTONE. Defines and describes the various sandstone properties.

CHAPTER FIVE: DECAY PROCESSES IN SANDSTONE BUILDINGS. Largely summarising previous work, this chapter outlines the main processes causing decay of building sandstones, and indicates which sandstone properties are thought to govern the resistance of sandstone to each decay process.

CHAPTER SIX: DURABILITY ASSESSMENT OF BUILDING SANDSTONES. Discussion and comparison of methods of assessing durability.

APPENDIX THREE: SANDSTONE DATA COLLECTION AND TESTING METHODS

Procedural details for conducting the various measurements and tests discussed in Chapter Six.

Aim 2:

To provide an inventory of the major historical and modern sources of building stone in Tasmania, incorporating data on stone properties influencing durability (as determined by sampling and testing).

A major proportion of the field and laboratory work undertaken in this project has been directed towards achievement of this aim, although as explained in Section (1.5) certain limitations in the data collected have been recognised subsequent to compilation of the inventory. The inventory is presented as follows:

CHAPTER THREE: TASMANIAN SANDSTONES. Based largely on previous work, an outline of the stratigraphic and geographic distribution of geological units containing sandstone suitable for use as building stone.

CHAPTER FOUR: TASMANIAN BUILDING SANDSTONE SOURCES - SUMMARY OF DATA. A brief summary of the data contained in Appendix One.

APPENDIX ONE: SANDSTONE SOURCE DATA SHEETS. Detailed listing of all data collected on building sandstone sources.

Aim 3:

To investigate the influence of depositional, diagenetic, tectonic and weathering environments in producing those sandstone properties which govern quality and durability. The ultimate aim of such work is to produce models of the geological environments in which the most durable building sandstones might have formed. Such models could then facilitate future exploration for high quality sandstone.

A large number of individual topics and investigations are included under this general aim. Due to the wide scope of the aim, and to the small amount of previous work directed specifically at producing models to facilitate exploration for durable building stone, many of the conclusions reached in this work are incomplete and tentative. However, an effort has been made to suggest as many models as possible, with a view to indicating worthwhile directions for future research.

The work undertaken towards achievement of this aim comprises reviews of relevant existing information, descriptions of those original contributions which have been made during this project, and suggestions for future research. The work is presented as follows:

CHAPTER SEVEN: GEOLOGICAL CONTROLS ON QUALITY AND DURABILITY-RELATED SANDSTONE PROPERTIES. A presentation of all the work towards Aim 3 undertaken during this project.

CHAPTER NINE: FURTHER WORK. Recommendations as to future research directions likely to be of value in achieving Aim 3.

CHAPTER TWO

SANDSTONE

2.1 DEFINITION AND CLASSIFICATION OF SANDSTONES

Definitions of the term "sandstone" vary, but for the purpose of this thesis the term refers to clastic, predominantly siliceous sediments (Pettijohn *et al.*, 1973, p.170), whose grains have a mean diameter of between 1/16 and 2.0 millimetres (Berkman & Ryall 1976). The grains are generally bound together by a combination (in Tasmanian Triassic sandstones) of both a clay matrix and by chemically precipitated cements including silica and iron oxides or hydroxides.

There are many different ways to classify sandstones, and the classification system most appropriately applied in any particular study depends on the aspects of the sediment which are under consideration. No formal system has been devised to classify sandstones from the point of view of durability; a listing of relevant properties and test results must be used for such a purpose.

For general descriptive purposes, however, a sedimentological classification is useful. A common classification is that based on Folk (1974) and Pettijohn *et al.* (1973). This classification is based on the percentages of various clastic grain types present. Thus, to give the main end members, a quartz arenite has 95% or more quartz grains, an arkose has 25% or more feldspar grains, and a lithic arenite has 25% or more rock fragments. As a secondary criterion, the classification distinguishes between sandstones with less than 15% matrix ("arenites"), and those with more than 15% matrix ("wackes"). (In this context, "matrix" refers to clays plus clastic grains (silt) <0.06mm diameter.)

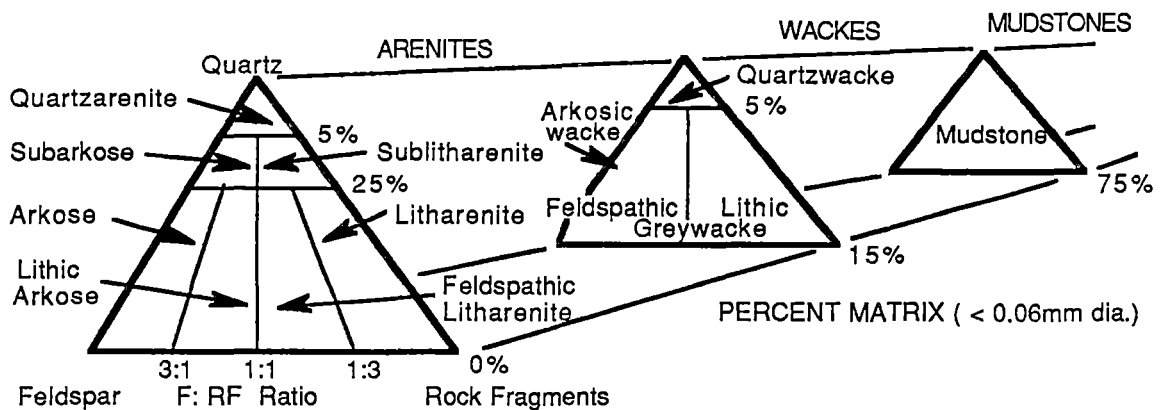


FIGURE 2.1 Classification of Sandstones, based on Folk (1974) and Pettijohn *et al.* (1973).

Definitions may vary between workers as to the cut-off points between arenites and wackes, and between arkoses, quartz- and lithic arenites. Under the above classification, many Tasmanian building stones would strictly be classified as "wackes", since they have clay matrices in excess of 15%. However, most Tasmanian workers have not described sandstones as wackes unless the clay content has been well in excess of 15%.

For this reason, in the present work the term arenite refers primarily to the composition of the clastic grains, and the term wacke (or greywacke) is only used in special cases (ie, the Sarah Island greywackes).

2.2 SANDSTONE CONSTITUENTS

2.2.1 Quartz

Silica (SiO_2). The dominant constituent of most Tasmanian sandstones. Because of the high chemical and physical stability of quartz compared to other minerals generally found in sandstones, the highest possible quartz content is desirable for building stone.

2.2.2 Feldspar

Small percentages (generally less than 5% by volume) of feldspar grains were found in most of the quartz arenites studied in this work. Microcline, plagioclase and orthoclase were identified in Tasmanian sandstones during this project.

Feldspars are detrimental to sandstone durability as they are chemically less stable than quartz and may alter to clay, thus softening the stone. In many Tasmanian quartz arenites, however, the feldspar content is low enough to have negligible effect.

2.2.3 Micas

Hydrous aluminosilicates closely related to clay minerals. The most common micas in Tasmanian sandstones are biotite and muscovite. Muscovite is similar in composition (but somewhat different in structure) from the clay mineral illite (also known as "clay-mica" or "hydromica"). Muscovite and illite are most obviously differentiated by their grainsizes: grains larger than 2 microns (0.002mm) diameter are called muscovite, while grains smaller than 2 microns are defined as "clay", and called illite (Carroll 1970).

Very fine grained mica is known as sericite, and may be difficult to distinguish from true clay under the microscope.

Through diagenesis and weathering micas may convert to clay (or vice versa), so that mica content may be relevant to stone durability in this way. However, since Tasmanian sandstones usually contain only one or two percent mica this particular effect is probably limited.

Rather, it is the manner in which mica is distributed in sandstone which has the most important bearing on durability: if mica is randomly distributed then it's presence is of little consequence. On the other hand, when (as commonly occurs) the mica is concentrated on particular bedding planes, the sheet-like nature of the mica grains will cause the bedding plane to be a site of easy splitting (and thus of lowered durability).

2.2.4 Clays

Clays are sheet-structured ("phyllosilicate") aluminosilicates, often hydrous, of grain sizes smaller than 2 microns (0.002 millimetres). While there are some differences in atomic structure, micas can be broadly regarded as similar materials of larger grain size.

Clays are a major constituent of all Tasmanian sandstones, and have an important influence on durability. They influence the strength and porosity of sandstone, and the response of

stone to wetting/drying cycles.

The structures of clays are based, with few exceptions, upon composite layers having either tetrahedrally or octahedrally coordinated cations (Berry & Mason 1959). The tetrahedral layers have SiO_4 tetrahedra linked by sharing three of the four oxygens, and are referred to as "the silica sheet". Al may replace up to half the Si in these layers.

The octahedral layers have cations (usually Al, Mg or Fe) with O or OH anions arranged around them in an octahedral structure. The octahedral layers may have either a dioctahedral arrangement (two cations for each six OH anions, characteristic of the structure of the mineral gibbsite), or a trioctahedral arrangement (three cations for each six OH anions, characteristic of the mineral brucite).

Since the dimensions of the tetrahedral and octahedral layers are similar, composite stacks of these layers are easily formed. Such stacks may have a two layer structure (one layer of each type) or a three layer structure (an octahedral layer sandwiched between two tetrahedral layers).

The different groups of clay minerals are largely defined by the structural permutations allowed by these varying clay layer structures; that is by the mode of stacking of the sheets (two or three layer), and by the nature of the octahedral layers (gibbsite-type or brucite-type). In addition, considerable variability in the chemical composition and physical size of clays is produced by isomorphous cation replacement, and by variable numbers of water molecules between the layers.

All clays display the property of expanding and contracting with water absorption and release. Clays with non-expanding lattices (eg, kaolinite and illite) take up water on external clay crystal surfaces, causing some expansion of clay aggregates. However, the greatest expansion with wetting is achieved with "expanding lattice" clays (smectite, vermiculite, halloysite, swelling chlorite and mixed layer illite/smectite). These latter clays take up water between unit layers within clay crystals. This intra-crystalline swelling causes greater swelling of clay aggregates than does inter-crystalline swelling (Gillot, 1987).

Clays may occur in sandstone as interstitial pore-filling matrix, detrital pellets, pore-lining grain coatings, intergranular layers and films, and as altered feldspar or mica grains.

Due to their sheet structure clays have very large surface areas, and tend to exchange ions readily with their environment by isomorphous cation replacement so as to remain in chemical equilibrium. Thus, although much of the clay in sandstones may be ultimately of detrital origin, it changes composition over time in response to changing pore-water compositions. This can lead to significant authigenic clay growth in sandstones.

The following clay types are those most commonly found in Tasmanian sandstones (Clay mineralogy references used include Folk 1974, Berry & Mason 1959, Deer *et al.* 1966, and Weaver & Pollard 1973):

(A) Illite

A clay, similar in structure to muscovite mica, which has a three layer structure consisting of a dioctahedral (gibbsite) layer sandwiched between two tetrahedral silica layers.

Illite is a K-enriched hydrous aluminosilicate which occurs almost ubiquitously in

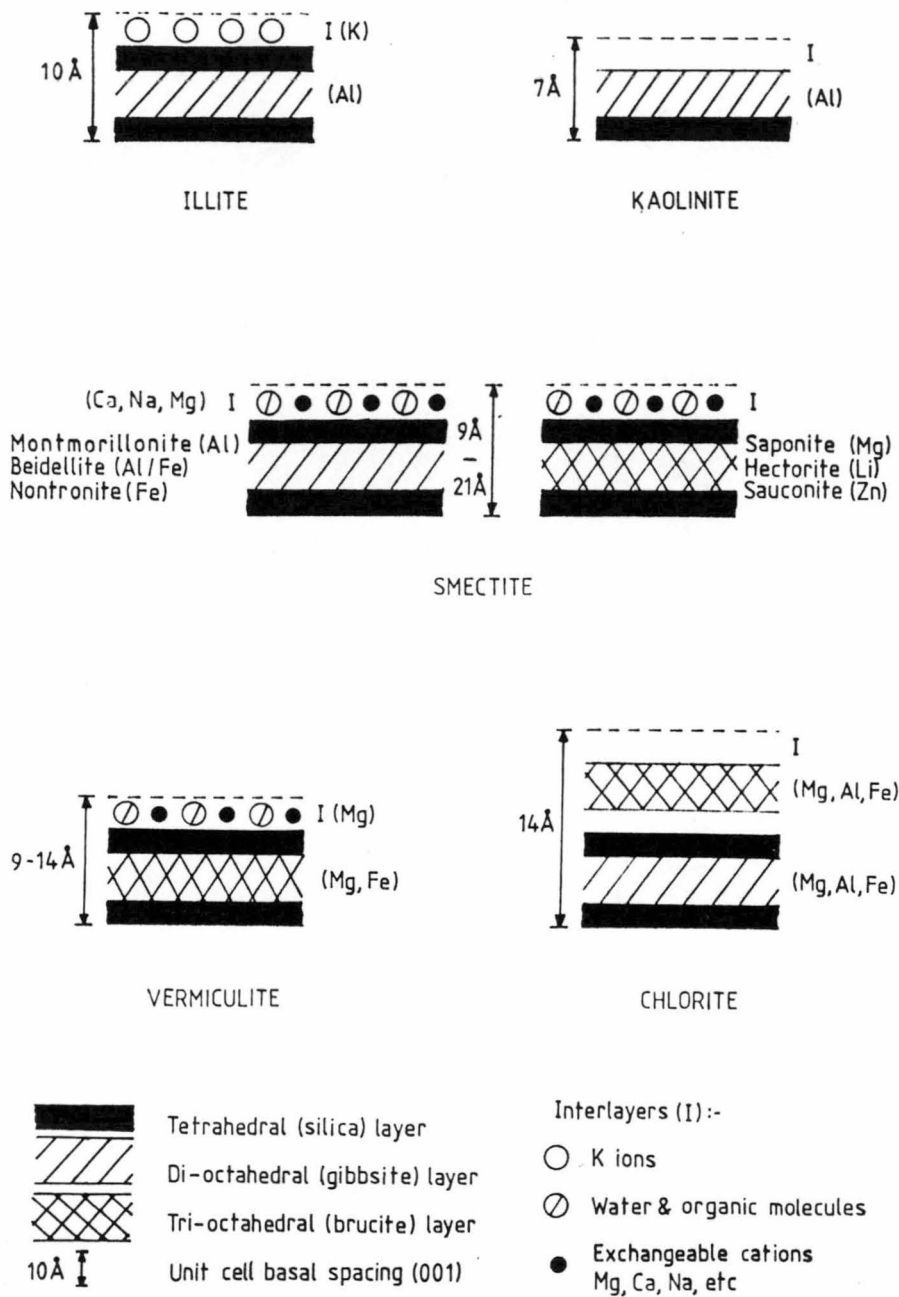
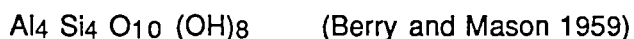


FIGURE 2.2 Representative structures of the major clay groups

Tasmanian sandstones. Illite typically differs from muscovite in having more silica and less potassium. However, considerable chemical variations occur in illites; K-content may vary, and Al may be partly replaced by Mg and Fe. The presence of interlayer K ions in illite prevents the entry into the structure of water and organic liquids, so that the clay is not expandable by intra-crystalline swelling. Illites also have a relatively low cation exchange capability (Deer, Howie & Zussman, 1966).

(B) Kaolinite

A hydrous aluminosilicate having a two layer structure with a dioctahedral (gibbsite) layer. Little or no atomic substitution occurs, so that it usually corresponds closely to the simple formula:



In contrast to illite, smectite, vermiculite and chlorite, kaolinite is lacking in K, Mg and Fe. Kaolinite is the commonest of four related clay species which differ only in the stacking sequence of their layers, the other related species being dickite, nacrite and halloysite (halloysite also has a single layer of water molecules between its structural sheets). Collectively, the four are known as kandites. Halloysite occurs rarely in Tasmanian sandstones (Cobbs Hill Quarry, Source 23).

(C) Smectite ("montmorillonite") and mixed layer illite/smectite

Smectites are a group of Mg-rich clay minerals which have the property of expanding and collapsing their crystal lattices by absorption and release of water. These clay minerals are often loosely referred to as "montmorillonite", although montmorillonite is only one variety of smectite (albeit the most common).

Smectites are hydrous aluminosilicates which are related by a common structure and by similar chemical and physical properties. Smectites have a three layer structure consisting of octahedral layers (which may be either di- or tri-octahedral; see below) sandwiched between tetrahedral silica layers. Interlayers contain exchangeable water molecules and some other exchangeable cations.

An important difference between smectites, and clays such as illite or vermiculite, is that the layers are not bonded by K⁺ ions (as in illite) or Mg ⁺² ions (as in vermiculite), but rather by water molecules and some exchangeable cations. The interlayers readily exchange their water molecules with the environment, taking up or releasing water as the environment is wetted or dried under normal climatic cycles. Expansion and contraction of the interlayers (and thus of whole smectite grains) results from this, and can over many cycles lead to breakdown of intergranular bonds in sandstones containing smectite in their matrices.

Smectite may be more or less detrimental to sandstone durability depending on the manner of its occurrence in sandstone. Discrete rounded microscopic pellets of smectite can be relatively benign, whereas even small quantities of smectite can be very detrimental if present as thin intergranular films (see Section 2.3.4).

Under normal conditions, smectite (001) basal spacing (one layer plus interlayer) is between 12 and 15 (usually 15) Angstrom units (Å) thick. When excessively wetted, the

basal spacing may expand up to 21 Å, while complete dehydration may cause collapse to 9 Å. The amount of water smectite can take up is partly determined by the type of interlayer cations, eg, Na-montmorillonite can expand to a far greater extent (up to 21 Å) than can Ca-montmorillonite (up to 15.5 Å). As a characteristic test, absorption of ethylene glycol into the interlayers causes the basal spacing of montmorillonite to expand to 17 Å.

Considerable chemical variation occurs in smectites: individual smectite species can be characterised as follows:

Montmorillonite

Most common variety, having di-octahedral (gibbsite-type) octahedral layers. A species rich in aluminium (in the layers) and containing Ca and Mg and/or Na in the interlayers. Ca-montmorillonite is the most common form in nature (Deer *et al.* 1966).

Nontronite

A variety having di-octahedral layers; an iron-rich species, in which the iron partially substitutes for aluminium in the layers. Beidellite is another di-octahedral species intermediate in Al/Fe content between montmorillonite and nontronite.

Saponite, hectorite, sauconite

Species having tri-octahedral (brucite-type) octahedral layers. Al in the layers is wholly or partially substituted by Mg, Li and Zn, respectively.

Much naturally occurring smectite is not pure, but is a "mixed layer illite/smectite" clay. In such clays, individual layer/interlayer unit cells of smectite may alternate with layers of illite. The illite/smectite layers may occur in a regular alternating pattern, or at random.

Mixed layer illite/smectites are recognisable on X-Ray diffractograms by the unusual (and variable) shapes of the peaks produced by diffraction from layers with distinctive basal spacings. Generally, mixed layer illite/smectite appears on diffractograms as a broad humpy peak, with a main peak at 10 Å (illite) and another main peak anywhere between 10 and 15 Å. When ethylene glycol is added, these separate into a distinct illite peak at 10 Å and a distinct smectite peak at 17 Å (see also Srodon 1981).

A large proportion of the smectite in sandstones studied in this project has been mixed layer illite/smectite.

(D)Vermiculite

The term "vermiculite" encompasses a variety of chemical compositions, but is characterised by a three layered structure having tri-octahedral (brucite-type) octahedral layers.

Vermiculites are Mg and Fe-rich expandable clays similar to smectite but having a larger layer charge (Weaver & Pollard 1973). Vermiculites commonly contain Mg in their interlayer positions and, like smectite, may expand and contract by absorption and release of water, certain organic liquids and exchangeable cations in the interlayer positions.

However, although it is an expandable clay, vermiculite is unlike smectite in that it does not display expansion/contraction behaviour under normal environmental conditions. It is thus not a detrimental swelling clay in the same way smectite is.

Under normal environmental conditions vermiculite is in its fully hydrated state, with a unit cell basal spacing of 14 Å, and thus will not expand further upon addition of water or ethylene glycol. Only upon being strongly heated will vermiculite dehydrate and collapse in a series of steps until collapsing to 10 or even 9 Å at about 550° C.

Vermiculites rehydrate more readily than smectites (Deer *et al.* 1966,p.273), which means that under normal conditions they simply remain in their fully hydrated state.

Alan Spry (*pers. comm.* 1988) notes that sandstones rich in vermiculite often have low durability. However, it is not clear that vermiculite would lower durability simply in virtue of its mineralogical properties; rather, it seems likely that significant vermiculite content may in some cases be related to weak intergranular texture, and so lower durability for that reason.

Vermiculite has been identified in a significant number of cases in Tasmanian Triassic sandstones.

(E) Chlorite

Chlorite is characterised by a three-layer structure consisting of alternating tri-octahedral (brucite-type) layers and mica layers (Berry & Mason 1959). The chemical composition and properties of chlorites vary widely. They are a group of hydrous silicates containing Mg, Al and Fe in widely varying proportions.

Chlorite has been identified in a small proportion of Tasmanian Lower Triassic sandstones.

2.2.5 Cements and stains

Minerals chemically precipitated in sandstones subsequent to their deposition. They may act as binding agents, increasing the strength of the sediment, and/or may impart a colouration. The most common mineral cements/stains in Tasmanian sandstones are silica and iron hydroxides. Minor manganese oxide staining may occur. Carbonate cementation appears to be rare or absent in Tasmanian Lower Triassic building sandstones, although carbonate cementation is known in the Upper Permian Cygnet Coal Measures sandstones (Forsyth, *in* Burrett & Martin 1989), and in parts of the Upper Triassic lithic sandstone sequence (M.R.Banks, *pers. Comm.* 1990).

(A) Silica cementation

Silica cementation occurs through precipitation of silica as authigenic overgrowths on or between quartz grains. This process may increase stone strength and reduce porosity (see Sections 2.3.4, 7.9.1, 7.10.1).

Cementation by silica overgrowths between separated grains is distinguished from the welding resulting from the pressure solution and re-precipitation which occurs when quartz grains are directly appressed or mutually impinging (Spry 1976).

(B) Iron cementation (staining)

Ferruginous minerals (iron oxides or hydroxides) may precipitate in sandstones under oxidising conditions in which pore-waters contain iron. Iron oxides and hydroxides impart yellow, brown, red and (rarely) black colourations to sandstones.

Common precipitation patterns include the attractive concentric ring patterns known as "Liesegang Rings", often centred on fractures or joints along which iron-bearing waters have moved. Other common patterns include irregular patches, bands along bedding, spots and nodules, as well as uniform overall ("bulk") colourations.

Microscopic examination reveals that iron oxides and hydroxides precipitate as small dense brown to black cementing masses in intergranular spaces, as thin coatings on quartz (or other) grains, and as fine diffuse stainings of the clay matrix. The latter may be due to adsorption of iron ions on clay particle surfaces (Blatt *et al.* 1972, p.365), and/or to partial breakdown of iron-rich clays to precipitate the iron oxides or hydroxides.

The iron minerals most commonly precipitated are haematite (iron oxide, Fe_2O_3) and goethite (iron hydroxide, $\text{FeO} \cdot \text{OH}$). Goethite may occur in an amorphous or cryptocrystalline form known as limonite. Goethite may form haematite by dehydration.

Goethite has been identified in many Tasmanian sandstones (by XRD) during this project, and also by Spry (1983). It is possible that haematite also occurs, but it has not been identified and is probably minor. Some black stains occurring in Tasmanian sandstones may be iron oxides such as black haematite, ilmenite or magnetite.

(C) Manganese staining

Under highly oxidising conditions, manganese oxide (pyrolusite, MnO_2) can precipitate in sandstones as a black stain. An interesting form of manganese staining is the dendritic pattern which may form on bedding planes and fracture surfaces, and can extend into the body of stone as three-dimensional dendritic branches. More commonly, manganese oxide precipitates as thin black films on joint surfaces, or as black spots and patches within the fabric of the stone.

(D) Other stains

Weathering of pyrite or marcasite within sandstone may lead to formation of black patches (Threader 1982).

2.2.6 Other minerals

A number of other minerals are known as rare or minor constituents of Tasmanian sandstones.

Graphite occurs as an accessory mineral, and may form fine black bedding laminations which split easily. Magnetite, tourmaline, rutile, anatase, zircon, garnet, ilmenite, calcite, siderite, halite, epsomite and gypsum have all been recorded, although usually in trace amounts only (Spry & Banks 1962, Spry 1983, Sharples 1984, Forsyth 1987).

2.3 TEXTURAL PROPERTIES

In this investigation only two textural properties, grainsize and sorting, were determined for all specimens studied, although other textural properties such as grainshape, orientation, grain packing, intergranular texture and pore-size distribution also have a major influence on properties such as porosity and strength.

2.3.1 Grainsize

In this work, grainsize refers to the average (mean) diameter of quartz grains in a sandstone. The following categories - which differ slightly from those used by Spry (1983) - are employed in this work (*from* Berkman & Ryall 1976).

Grainsize	Average grain diameter (mm)
Very coarse grained	1.0 - 2.0
Coarse grained	0.5 - 1.0
Medium grained	0.25 - 0.5
Fine grained	0.125 - 0.25
Very fine grained	0.0625 - 0.125

Sandstones in the medium and fine grainsize categories are normally found to be the most aesthetically pleasing for building purposes.

2.3.2 Sorting

Although sorting can be precisely defined mathematically by laborious measurements of large numbers of individual grains, for most purposes a visual estimate of sorting is adequate. The following sorting categories are commonly used (phi standard deviations from Pettijohn *et al.* 1973):

- Well sorted - Majority of grains within a few percent of average diameter (0.0 to 0.5 phi (Ø) standard deviation).
- Moderately sorted - Most grains within 50% of average diameter (0.5 to 1.0 phi standard deviation).
- Poorly sorted - Very wide grainsize variations (>1.0 phi standard deviation).

Poorer sorting is often related to a higher clay content, and thus to a lower stone strength. In addition the greater textural uniformity of better sorted building sandstones is preferred for aesthetic reasons

2.3.3 Grain-shape and orientation (fabric)

Grainshape refers to the sphericity and roundness of clastic sand grains. Sphericity is the degree to which a grain's shape approaches that of a sphere. Grains with low sphericity may approach discoid or rod-like shapes, and consequently are more susceptible to forming a strongly aligned or oriented fabric with significant strength anisotropy. It is not unusual for certain minerals (eg platy mica grains) to have a strong common orientation while other mineral grains in the same sample, such as quartz, may have little common orientation.

Roundness refers to the degree of angularity of grain edges and corners. Grain roundness yields information on the sandstone's depositional regime. Whilst original quartz

grain shapes in Tasmanian sandstones were often well-rounded (as indicated by "dust rings" and some uncemented grains), authigenic quartz overgrowths produce angular crystal boundaries where the overgrowth is in contact with clay or pores, and irregular or planar boundaries may form where grains are pressed against one another.

2.3.4 Inter-Granular Texture

Although not determined for most of the samples studied in this project, this property has the major influence on stone strength and porosity (see Chapter Seven).

According to Spry (1976, and 1983, p.30 & 42), although the relative total proportions of quartz and clay influence strength, the major determinants of strength are textural: of greatest importance is the proportion of grain contacts between quartz grains (quartz-quartz (Q-Q) boundaries), compared to those between quartz grains and intergranular clay (quartz-clay (Q-C) boundaries). Q-Q contacts are normally stronger than Q-C contacts, since clay is a weaker material.

Spry (1983, p.30 & figs 7 & 8) showed that compressive strength tends to increase with an increasing proportion of Q-Q contacts, and also that the ratio of wet/dry compressive strength increases with an increasing proportion of Q-Q contacts.

The proportion of various contact types in a sandstone can produce textures ranging from mechanically strong "closed frameworks" (clasts mainly in contact with each other) to mechanically weak "open frameworks" (clasts "floating" in clay matrix with little direct mutual contact). Tasmanian Triassic and Permian sandstones have predominantly closed framework textures, with most of the clay volume in the interstitial spaces.

Quartz-quartz grain contacts may be just touching or interlocking (weak contacts), welded by appression and interpenetration (due to pressure solution of silica), or non-appressed grains may be cemented by authigenic silica overgrowths. Spry (1976) was not able to find any difference in strength between the welded and the cemented Q-Q contact types. However, while Q-Q contacts are generally stronger than Q-C contacts, they are likely to vary in strength since the mere butting-together of two quartz masses does not necessarily produce a strong welding or cementing. Nearly invisible defects such as micro-cracks or extremely thin clay films along apparent Q-Q boundaries can significantly reduce contact strength (Spry 1976).

Again, while the "glittering" often seen in hand specimens does indeed indicate the presence of authigenic silica overgrowths, it does not necessarily indicate strongly cemented stone: the glittering is due to well-formed authigenic crystal faces, which can only form when the overgrowth grows into a pore space, or in contact with soft clay. The glittering faces thus result from weak Q-C or Q-void contacts (Spry, *pers. comm.*, 1989). Of course, a high proportion of "glittering" faces is suggestive of a high proportion of cemented Q-Q contacts.

The effect of clay upon stone strength depends partly upon the proportion of clay present, but more importantly upon the morphology and distribution of the clay (Spry 1983). Thus, discrete microscopic clay pellets or interstitial clay masses may not greatly decrease stone strength, even if present in moderate amounts. (Even smectite swelling clay is relatively benign if it is only present as pellets.)

On the other hand, even small amounts of clay can significantly decrease stone strength if the clay occurs as intergranular clay layers or films separating quartz grains.

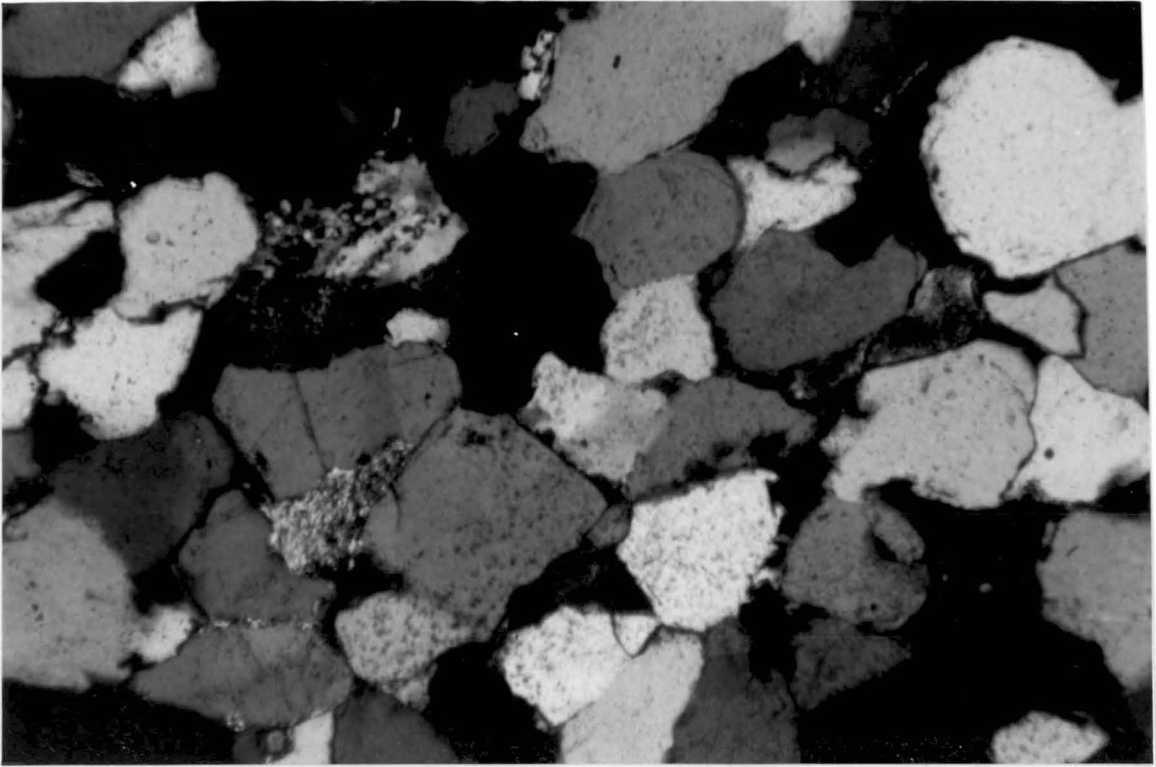


Plate 2.1: Strong intergranular texture: note high proportion of quartz-quartz grain contacts, including irregular welded contacts and quartz cement (indicated by fine "dust rings"). Spec. C/1/1, Cobbs Hill Quarry, Source 23; Scale x 100, crossed nicols.

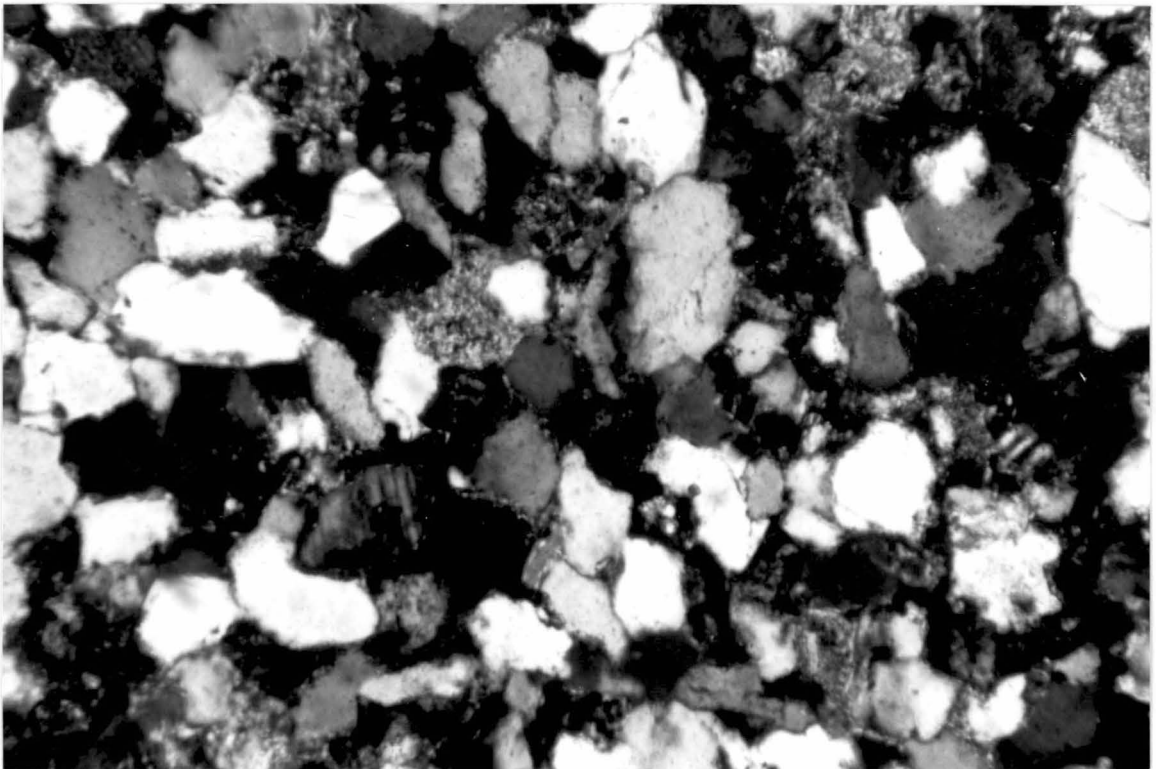


Plate 2.2: Weak intergranular texture: note high proportion of clay ("speckled" interstitial masses & intergranular layers). Specimen also contains high proportion of ferruginous cement (black masses). See also Plate (7.25). Specimen 51/2/7, Elderslie Quarry, Source 26; Scale x 100, crossed nicols.

Intergranular clay films, even when extremely thin, are mechanically weak, have high micro-porosity (Spry 1983), and if present to a significant degree can result in a marked reduction of stone strength when wetted (ie, low wet/dry strength ratios) (Spry, *pers.comm.* 1989). The presence of smectite swelling clay in intergranular films is particularly detrimental to stone durability.

Significant quantities of dense intergranular ferruginous cement may serve to increase stone strength, although in most cases the effect of ferruginous cement is probably outweighed by that of quartz and clay bonding (see Section 7.9.1).

Examples of the various contact morphologies discussed above are illustrated in Plates (2.1) & (2.2), and in Appendix Three, Figure (A 3.3).

2.4 MACROSCOPIC PROPERTIES

The macroscopic properties of sandstone are those properties which are apparent in outcrop. The following are those macroscopic properties of Tasmanian sandstones which are most important from the point of view of ease of quarrying, durability and aesthetic appearance.

2.4.1 Coherence

The ease with which sand grains can be rubbed off fresh surfaces by hand. Coherence is proportional to stone strength, since it is determined by the strength of grain bonds. Three categories of coherence are commonly used:

Friable	-many grains rub off easily by hand.
Moderate coherence	-a few grains rub off by hand.
Coherent	-very few, or no, grains rub off by hand.

2.4.2 Colour

Sandstone colours are classified in this work according to the Munsell classification system (Munsell Color Company, Maryland, U.S.A.), as used on the "Rock Color Chart" issued by the Geological Society of America.

Sandstone normally takes on a darker colour wet than it does dry. In this work, colours quoted were determined on specimens which were "dry" under average atmospheric humidity.

In the quartz arenites mainly dealt with in this project, stone colour is determined by clast type, clay matrix types, and by the occurrence of iron (sometimes manganese) oxides and hydroxides.

In describing the colour of sandstones two components are distinguished: an overall background "bulk" colouration, and the coloured lines, patches, spots, etc (usually ferruginous stains) which may be superimposed on the bulk colour.

In the absence of ferruginous stains, stone colour is generally a uniform white to light grey bulk colour controlled by the dominantly quartz clast composition and the white clay matrix (see Plate 4.1). If chlorite (commonly green in colour; Deer, Howie & Zussman 1966, p.237) is present, the stone may sometimes have a greenish tinge (eg, Kangaroo

Point Green Sandstone).

In the presence of ferruginous stains the stone may take a yellow, brown or even reddish tinge. These colours may produce a uniform bulk colouration (Plate 4.8), or may occur in lines, bands, patches or spots superimposed on a bulk colour which is commonly the light grey of "unstained" sandstone (Plate 4.9).

Although rare in Tasmanian sandstones, some New South Wales sandstones containing siderite may rapidly darken from a light to a darker brown colour after quarrying, due to oxidation of the siderite.

Impure sandstones rich in materials such as volcanic clasts and chlorite may take differing colours, such as the dark grey-green colour of the Tasmanian Late Triassic lithic arenites.

2.4.3 Bedding

"Bedding" is the depositional layering or stratification of sandstone, and may be marked by differences in texture, colour, composition or structure.

The types of bedding most commonly encountered in Tasmanian sandstones are massive, cross-bedded and planar (defined below). For the purposes of this work, layers are known as "laminae" if thinner than 10 millimetres, and "beds" if thicker than 10 mm.

Bedding is an important feature of building sandstone since it gives rise to a strength anisotropy, with stone tending to break most easily along the direction of bedding. Distinct bedding planes can be important planes of weakness as they commonly have thin coatings of fine silt, clay, graphite or mica. Splitting may occur along such planes prior to quarrying due to the unloading effects of erosion.

It is important to be able to quarry thick layers of sandstone free of such major splitting planes. Further, even when major splitting planes are not present (and even if bedding is massive or indistinct), it is always important to lay stone in buildings with bedding direction horizontal (normal to the direction of greatest stress), since some strength anisotropy is usually still present. Bedding direction should be marked on stone blocks prior to extraction from the quarry, since it may be difficult to discern on freshly cut surfaces.

Massively bedded sandstone comprises thick beds with no internal layering structure, and is the ideal for large dimension blocks since it has minimum strength anisotropy (see Plate 7.2). It should be recognised, however, that many supposed massive sandstones are in fact very faintly plane- or cross-bedded. For instance, very faint planar banding can be discerned in some outcrops of the "massive" beds at the Elderslie, Oatlands and Linden quarries. Pettijohn *et al.* (1973, p.107) suggested that true massive beds are very rare.

Cross-bedded sandstone consists of successive beds, or "sets", with an internal structure of inclined laminations (see Plate 7.3). The internal laminations may develop a tendency to split after some years in a building if they are distinct and swelling clay, mica or graphite is present. However laminations are often indistinct and may not be significant lines of weakness; rather it is the planes bounding sets which are most susceptible to splitting. The tendency to split along bounding planes varies, and many cross-bedded sandstones show minimal splitting tendency over several cross-bed sets (eg, Buckland Quarry). Such cross-bedded sandstone may be adequate for extraction of large dimension blocks.

Planar bedded sandstones have simple horizontal bedding planes which are often coated with clay, silt and/or mica, and which may have primary current lineations which facilitate splitting (see Plate 4.11). They commonly split easily into thin slabs and may be ideal for paving and ornamental slabs. They are rarely usable as large dimension blocks.

Bedding structures are sometimes deformed by mechanical movement of sand shortly after deposition. A common deformation structure in Tasmanian sandstones is "oversteepened" or "overturned" cross-bedding, in which laminae are overturned in their upper parts. This is thought to be a result of shear stresses exerted on thixotropic sands by water currents. Other deformation structures include convoluted, "crinkled" and slumped bedding.

Deformation structures are no more detrimental to stone durability than cross-bedding of similar distinctness, and may enhance the attractiveness of the stone for certain uses.

2.4.4 Bedding Dip

Most Tasmanian (Triassic and Permian) building sandstones have *in situ* bedding dip angles of less than 15° from horizontal. Since bedding planes may be lines of weakness, and are in any case the planes along which stone is normally removed from the quarry, a high dip angle (say 20 - 30°) would make the stone difficult and perhaps dangerous to quarry.

2.4.5 Textural "defects"

While the following sedimentary features normally have minimal detrimental effect on stone durability (unless present in excessive proportions), they are considered aesthetically undesirable.

(A) Quartz pebbles

Quartz clasts of significantly larger diameter than the grain size of the containing stone; they may occur scattered randomly or concentrated in bands; relatively insignificant occurrences in the sandstone horizons normally quarried in Tasmania.

(B) Clay pellets

Most commonly occur as flat, rounded or ovoid discs elongated along bedding direction. May be scattered randomly or concentrated in bands (in the latter case they may indeed be detrimental to stone strength). The majority of Tasmanian building stones contain at least a small proportion of scattered clay pellets.

(C) Mudbands

Thin mud bands can occur in otherwise good sandstone deposits. They constitute significant weaknesses, and must always be avoided entirely.

(D) Concretions

These occur as discrete, scattered rounded bodies ranging from a few millimetres to several centimetres or more diameter. The most common type are iron oxide concretions which have precipitated *in situ* as a result of diagenetic processes. Considered aesthetically undesirable.

(E) Porous spots

Spherical patches scattered randomly through some sandstones, and varying in diameter from about 10 mm to several tens of millimetres. They commonly weather to a slightly darker colour than the surrounding sandstone, and tend to be more porous and of lower strength (see Plate 7.9). They can weather out leaving distinct "dimples".

2.4.6 Faulting, Jointing and Fracturing

Faults, joints and fractures are breaks in rock masses. They are very important since their spacing determines the maximum size of unflawed blocks which can be quarried. No block containing a break can be used in building, since it will probably fail along the break under stress.

For the purposes of this work, the various types of break are classified as follows:

- Faults - Major breaks along which relative movement of rock masses has occurred.
- Joints - Breaks, generally planar, parallel and evenly spaced, with little or no relative movement of rock masses.
- Fractures - Minor breaks, often irregular and unevenly spaced, with no relative movement of rock masses. May be deep cracks extending through a body of rock, or simply superficial weathering-related fractures.

Faults are major breaks which may include zones of shattered rock up to several metres wide. Faults are not commonly encountered in Tasmanian sandstone quarries.

Joints are the most important type of break from the point of view of sandstone quarrying, as no large sandstone mass is ever totally free of joints. Joints occur in sets of parallel or sub-parallel planes (Plate 7.1). Jointing is the means by which a rock mass relieves stresses transmitted through it by phenomena such as folding, faulting, epeirogenic movements, unloading due to erosion of overburden, and intrusion of magmatic bodies (including both the physical movement associated with intrusions, and the effect of heating and cooling stresses).

The same body of rock can be affected by different joint-forming stresses at different times, and it is common to find a number of joint sets at various angles to one other. In Tasmanian sandstones a common situation is the existence of two or more sub-vertical joint sets, causing the stone to break into blocky prisms.

It is common to find fractures on the surface of naturally weathered outcrops which only extend 50mm or less into the stone. Random, sparsely distributed superficial fractures may be of little significance.

However, closely-spaced superficial fractures on some outcrops may form polygonal fracture networks known as "pachydermal" or "elephant skin" fracturing (see Plate 7.2). Pachydermal fracturing may result from surface stress-release in stone having a high degree of dimensional instability (Section 2.5.9) as a result of a texture dominated by intergranular clay layers and films (see Sections 2.3.4 and 7.9.3), and is therefore thought to indicate sandstone of low quality for building purposes.

In such stone, the present work suggests that dessication upon exposure causes significant shrinkage of surface layers producing a contractive strain which is released by fracturing of the weathered surface.

The strength of joints and fractures may vary; "open" breaks which are clean or have only thin films of ferruginous (or other) minerals are generally weak, whereas joints strongly cemented by iron oxides or other materials may actually be stronger than the surrounding stone (as in the Sarah Island sandstones). In either case joints and fractures constitute a strength inhomogeneity along or adjacent to which stone will tend to break.

2.5 PHYSICAL PROPERTIES

2.5.1 Water Absorption and Effective Porosity

Sandstone absorbs water into void pore spaces and clay masses (see Section 7.10.1). The ultimate amount of water which can be absorbed into a rock is known as its "absolute porosity". However, some of this absolute porosity will normally be inaccessible to water, due to factors such as the lack of interconnectedness between some pores.

The volume of water which can be absorbed into interconnected pores and clay masses under conditions of normal pressure and temperature is a quantity which is of greatest relevance to stone durability, since it determines the susceptibility of the stone to salt crystallisation or clay swelling. This quantity is measured as the equivalent properties of "effective porosity" (volume % water uptake) or "water absorption" (weight % water uptake). Measurement techniques are discussed in Appendix Three.

The term "porosity" is to some extent a misnomer, since water uptake in Tasmanian sandstones is not only due to actual void pore spaces, but also to clays; however in this thesis the term is used for convenience to cover both sites of water absorption.

There is some variation in porosity and water absorption terminology used in the literature. The following table compares the terminology of the present work with that used by Spry (1983), Standards Association of Australia (1983), and Spry (1988):

<u>THIS WORK</u>	<u>SPRY (1983)</u>	<u>SAA (1983)</u>	<u>SPRY (1988)</u>
Absolute Porosity (vol.%)	Absolute (Total) Porosity(vol%)	Absolute (Total) Porosity(vol%)	Absolute (Total) Porosity(vol%)
-	Effective Porosity(vol%) = Porosity to gas (close to abs. porosity)	Gas Porosity	-
Effective Porosity (vol.%)	Water Absorption (vol%), OR Apparent Porosity(vol%)	Apparent Porosity(vol%)	Water Absorption(vol%) = Apparent OR Effective Porosity (vol%)
Water Absorption (wt%)	-	Water Absorption(wt%)	Water Absorption (wt%)

Effective porosity and water absorption show the relationship (adapted from Spry 1988):

$$\text{effective porosity (vol.\%)} = \text{water absorption (wt.\%)} \times \text{dry bulk density (t/m}^3\text{)}$$

Factors such as pore-size distribution are considered to be important in the response of stone to decay agents, as well as the simple effective porosities. It is considered that a high

proportion of very fine pores may result in lower durability than a similar proportion of coarse pores would, for instance (J.Heiman, *pers. comm.* to P.Spratt 1985). Such aspects of porosity have not been studied in this work, but can be measured by mercury porosimetry or the suction plate technique (Anon. 1975). Saturation co-efficient (ratio of water absorption to porosity) also gives a crude measure of pore structure (Ashurst & Dimes, 1984: "Stone in Building" - Swindon Press Ltd.)

In Tasmanian Triassic sandstones, effective porosities range from approximately 8.0 to 18.0 vol.%, and water absorptions from approximately 4.0 to 8.0 wt.% (See Appendix One).

Permeability and rate of water uptake

Permeability is the rate at which water can move through stone, and has not been measured in this work. Spry (1983) found that in many cases, durability decreased as permeability increased. This is probably because permeability normally increases as porosity increases, since with a greater proportion of pores in a stone, interconnection between pores will become more common.

However, Spry also found cases in which low durability stones had low permeability, and high durability stones had high permeability. Such complications may result in part from the fact that increasing clay content (which may both decrease durability and increase effective porosity due to water uptake in clay masses) can have the effect of lowering permeability

It appears that it is the amount of water which stone can hold (porosity) which is most important, rather than the rate at which it can take up that water (permeability).

Nevertheless, it is a valuable exercise to measure the rate at which water is absorbed into specimens during standard water absorption testing. This can be done by weighing specimens at regular intervals during the water absorption process. By using an arrangement wherein specimens are suspended from a balance during the first few hours of soaking, measurements can be taken every few minutes. This is particularly important in assessing the water uptake which can be expected during rainshowers (A.Spry *pers. comm.* 1983).

2.5.2 Bulk Rock Density

Bulk rock density is the mass per unit volume (including pores) of a rock (normally measured for dry rock and quoted in tonnes/cubic metre - t/m^3). It is dependent on the densities and proportions of the minerals present, and upon the porosity of the rock.

Dry bulk density is directly related to the amount of void pore spaces in the stone, and is measured during water absorption testing. In Tasmanian sandstones, measured wet bulk densities determined by the same test can be expected to show a more complex relationship, since water is taken up both into void pores and by expansion of clay masses.

2.5.3 Compressive strength

Compressive strength is the load per unit area under which a block fails in compression by shear or splitting (Winkler 1973). Near the earth's surface and in buildings compressive stresses are normally uniaxial (eg a top-loading situation); such stresses are also referred to as "unconfined". Confined (or "triaxial") stresses can develop in situations such as mountain-building regions, but will not be relevant to most engineering studies of building stone.

Compressive strength is measured in MegaPascals (MPa). The conversion from pounds per square inch (psi) is given below:

$$1 \text{ psi} = 0.006894 \text{ MPa}$$

Winkler (1973, p.40-41) ascribed a range of compressive strengths from 7.0 to 70.0 MPa to sandstones.

The properties of sandstones which influence compressive (and tensile) strength are discussed in Sections (2.3.4) and (7.9).

Sandstone compressive strength varies with stone wetness, being lowest in saturated stone (Záruba & Mencl 1976, Bell 1983). This effect is due to binding clays within the stone losing some of their strength when soaked with water. There may also be other effects resulting from behaviour of water in pore spaces. The greater the drop in strength with wetting (ie, the smaller the wet/dry strength ratio), the less durable a stone is likely to be.

The compressive strength of rock materials has been found to have a linear relationship to their tensile strength. Using Point Load Strength Index (Is50) as a measure of tensile strength (see Section 2.5.5 below), Broch & Franklin (1972) found that uniaxial compressive strength (UCS) could be related to Point Load Strength Index as below:

$$\text{UCS} = 24 \times (\text{Is50}) \quad \text{MPa}$$

Read *et al.* (1980) showed that this relationship is not precise, and that variations of 20% or more may occur in the conversion multiplier. The relationship should be considered unreliable for lower strength rocks (below 1.0 MPa Is50; see Section 2.5.5). While it is clear that a proportional relationship exists, and is of a linear character, the conversion multiplier needs to be determined by actual measurements for any related suite of samples.

In practical assessments of sandstone durability it is desirable but not absolutely essential to measure both compressive and tensile strength. For practical reasons, only tensile strength (as Point Load Strength Index) was measured in this study.

Even the weakest consolidated sandstones generally have sufficient compressive strength to withstand the compressive loadings experienced in normal buildings. On the other hand, as expounded elsewhere in this work, the stresses most likely to cause stone decay are the tensile stresses imposed on intergranular bonds by salt crystallisation and clay swelling. Tensile strength is the most direct measure of the stone's capacity to resist such stresses, and thus seems a more directly useful parameter to measure, although the available measuring technique for tensile strength is less precise (see Section 2.5.5).

2.5.4 Surface Hardness

The surface hardness of stone has been shown to be related to compressive strength in a sem logarithmic fashion (Winkler 1973, p.36). Surface hardness can be easily measured in the field using a Schmidt hammer which operates on a rebound principle.

Unfortunately, the readings obtained with the Schmidt Hammer may vary markedly depending on hammer orientation, surface wetness, surface shape and smoothness, degree of weathering or case-hardening, and other factors (*see* Day & Goudie 1977, Williams & Robinson 1983). It is thus very difficult to obtain meaningful results from natural outcrop or rough quarry faces, and in any case a large number of readings are required.

Measurement of surface hardness was attempted in this project, but was rejected as a useful field technique because of the above complications.

2.5.5 Tensile Strength - Point Load Strength Index

Tensile strength is "the degree of coherence of rock to resist the pulling force" (Winkler 1973,p.41), which is to say, it is a measure of the force required to cause a rock to fail in tension.

Winkler said that the tensile strength of a rock depends on the strength of the grains and of their binding cement. Spry (1983,p.30) noted that strength as a whole depends on the strength of the intergranular bonds, since quartz grain strength is not a limiting factor. The interface area between minerals and the type of bonding between them is of particular importance (see also Section 2.3.4).

As discussed in Section (2.5.3), tensile strength is of greater direct relevance to stone durability than compressive strength, and moreover there is a linear proportional relationship between the two strength parameters.

As with compressive strength, tensile strength may vary with the degree of wetting of stone (saturated stone having lower strength due to softening of clay bonds, and possibly to other effects of water in pore spaces.) and the ratio of wet/dry strength is an important indicator of likely durability. Tensile strength also varies with respect to bedding direction, normally being highest when the direction of tensional stress is parallel to bedding planes.

Direct measurement of tensile strength of rock is performed by attaching metal end caps to specimens with epoxy resins, and pulling these into tension with wires (Bell 1983,p.511). However, such direct measurements have tended to be unsatisfactory since the method of gripping the specimen introduces bending stresses. Accordingly, most measurement of tensile strength is carried out by indirect methods.

Measurement of flexural strength by inducing failure in bending gives a measure of flexural tensile strength which is somewhat higher than the strength obtained in direct tension. Another common method of indirect testing is the Brazilian test, in which a cylinder or disc of rock is compressively loaded from end to end in a diametrical plane along its axis. This test is based on the principle that most rocks fail in tension when one principal stress is compressive (Bell 1983). However, failure may occur by localised crushing along the axis of loading, rather than by diametral tension. The Brazilian test is considered to be useful for brittle materials, but may give erroneous results for other materials (Mellor & Hawkes 1971). Since sandstone is not generally a particularly brittle material, the Brazilian test is probably not a suitable one for it.

The Point Load Strength Test (Broch & Franklin 1972, *see also* Bell 1983 p.513) was used in this work to provide an indirect measurement of tensile strength known as the Point Load Strength Index (Is50, measured in MPa). This method is described in Appendix Three. In essence, the specimen is placed between two cone-shaped jaws (platens) and subjected to compression. As in the Brazilian test, tensile stresses are generated normal to the axis of loading, and the specimen experiences an induced tensile failure.

Broch & Franklin (1972) suggested that the following scale of Point Load Strength Indices be used to classify rock strength (this scale was adopted by the Standards Association of Australia in Addendum No.1, Feb.1978, to AS 1726-1975):

Rock Strength Class	Point Load Strength Index Is_{50} (MPa)	Equivalent Uniaxial Compressive Strength (MPa)
Extremely high	> 10	> 160
Very high	3 - 10	50 - 160
High	1 - 3	15 - 60
Medium	0.3 - 1	5 - 16
Low	0.1 - 0.3	1.6 - 16
Very low	0.03 - 0.1	0.5 - 1.6
Extremely low	< 0.03	< 0.5

(Note that the equivalent compressive strengths given by Broch & Franklin in this table do not always correspond to their suggested multiplication of $24 \times (Is_{50})$. The reason for this is not clear.)

Bieniawski (1975) gives mean Is_{50} values of 2.33 - 2.83 MPa as typical for sandstones. Many Tasmanian sandstones are weaker than this, but the more durable sandstones can be stronger.

The effects of specimen size and shape are more pronounced in tensile than in compressive testing, because in tension cracks open and give rise to large strength reductions, whereas in compression cracks close and so variations are reduced (Bell 1983, p.513). Greater variation in test results can thus be expected in tensile testing. Bell (1983, p.515) suggested limiting the use of Point Load Testing to rocks with Point Load Indices above 1.0 MPa, as the scatter of results may be unacceptably great below that strength.

2 5.6 Flexural Strength and Modulus of Rupture

These terms refer the resistance of rock to failure in bending, but are measured in different ways. Flexural strength is of particular relevance to the use of stone in thin veneers and paving tiles (Spry 1988), and would also be of importance in choosing stone for applications such as over-hanging ledges, parapets, etc.

The measurement of flexural strength requires an specialised testing apparatus which was not available for this work.

2.5.7 Ultrasonic Pulse Velocity

The Ultrasonic Pulse Velocity (UPV) of a material is the velocity with which a pulsed ultrasonic vibration travels through it, and is usually measured in metres/second. UPV can be measured in both the laboratory and field with an instrument such as the PUNDIT (Portable Ultrasonic Non-destructive Digital Indicating Tester).

The UPV of a material depends on it's density and elastic properties. It can therefore be

hypothesised that UPV in sandstones should be related to porosity (which is directly correlated with bulk density) and strength (which, as a function of the proportions and types of grains and grain bonding materials, should correlate with elasticity to some degree). There is thus likely to be some relationship between UPV and absolute percentages of clay, silica, and other minerals present, as well as with the proportions of grain contact types (quartz-quartz and quartz-clay) in a stone (see Section 2.3.4).

In addition, it has been found that fractures, discontinuities and inhomogeneities affect UPV readings.

Previous work (see Spry 1983,p.31) showed that there is indeed a broad correlation between sandstone UPV and both bulk density and the log of compressive strength, but that it is not sufficiently close to allow prediction of strength from UPV, except in closely related groups of specimens.

The present work (see Section 6.2.1 and Appendix Six) has shown that UPV correlates rather vaguely with the log of effective porosity (P), and somewhat better with the log of Point Load Strength Index (S), but shows virtually no correlation with absolute clay percentages alone (absolute silica % and grain contact type % data was unavailable when the calculations were made). The best correlation with UPV was obtained by the function of log (S/P), which gives 50% correlation.

In general, UPV increases with increasing strength, and decreases with increasing porosity.

There is generally a UPV anisotropy with respect to bedding. UPV tends to be lower normal to bedding, because bedding planes are discontinuities which slow the ultrasonic pulses transmitted across them.

As Spry (1983)noted, and as the present work confirms, the correlation of UPV with other stone properties is not close enough to allow accurate determination of those properties from UPV readings alone. However, UPV readings can give useful indication of variations in stone properties within a quarry or related suite of samples, particularly if a few reference samples are submitted to accurate laboratory testing of the properties in question.

2.5.8 Abrasion Resistance

Abrasion resistance is related to the strength of intergranular bonds, and is of significance in evaluating stone for use in paving (Spry 1988). It is determined by the Taber Abrasion Test, which is a specialised test (requiring a Taber Abraser) that was not conducted in this work.

2.5.9 Dimensional Instability

Some stones (notably marbles) suffer permanent change in dimensions after long-term wet dry and/or hot-cold cycling (Spry 1988). This may result in cracking, warping, shrinkage or expansion. Spry (1988) gave an upper limit of 0.1% linear dimensional change before problems are encountered (applicable to all stone types).

Sandstones may be affected by dimensional instability, manifesting as short-term dimensional changes and/or permanent expansion or contraction. This may be attributable at least in part to expansion and shrinkage of clays (even non-"swelling" clays expand and contract to some degree with wetting and drying; Gillot 1987), and to thermal expansion. Sandstones with an intergranular texture featuring a high proportion of intergranular clay

layers and films seem to experience greater dimensional instability than stone with a high proportion of (more rigid) quartz grain bonds (see Section 7.9.2).

Spry (1988) quoted results from a number of Australian sandstones which show both expansive and contractive behaviour. However the measurement technique is still under development at the time of writing, and it is still difficult for different operators to obtain reproducible results. The test was not attempted in this work.

CHAPTER THREE

TASMANIAN SANDSTONES

3.1 INTRODUCTION

Sandstones occur in numerous geological units of widely varying ages throughout Tasmania. Most of these units are unsuitable for use as building sandstones by reason of intense jointing and fracturing, unsuitable mineralogies (including excessive clay and lithic clast contents), interbedded mudstones, and other reasons.

To date, the only Tasmanian units which have been found to be suitable as building sandstones are the Permian and Triassic units described in this chapter. In the rare instances that other units have been used (eg, Cambrian greywacke sandstones used in the Sarah Island penitentiary, Source 20), experience has shown them to be unsuitable and of low durability.

Both the Permian and Triassic sandstones belong to the Parmeener Supergroup (Banks 1973), which is a thick sequence of Upper Carboniferous to Triassic sediments filling the Tasmania Basin. The Tasmania Basin now forms a broadly synclinal area plunging SSE, in which the Parmeener Supergroup sedimentary rocks are generally lying sub-horizontally (Banks, *in* Burrett & Martin, 1989,p.294). Parmeener Supergroup rocks outcrop in most parts of Tasmania, but, apart from the basal glaciogenic rocks, are generally thickest and most widespread in the central to south-eastern parts of the state.

The Parmeener Supergroup is divided into Lower (Upper Carboniferous to Permian) and Upper (Upper Permian to Triassic) subdivisions (Forsyth *et al.* 1974), which in turn can be sub-divided in the manner indicated in Table (3.1) and discussed in the following sections.

3.2 LOWER PARMEENER SUPERGROUP SANDSTONES

The Lower Parmeener Supergroup sequence consists of thick tillites at the base, overlain by some hundreds of metres of predominantly glacio-marine siltstones and mudstones, with minor interbeds of limestone, sandstone, conglomerate and coal.

As indicated in Table (3.1), the Lower Parmeener Supergroup has been subdivided (Clarke & Banks 1975) into Upper and Lower Marine sequences, with an intervening Lower Freshwater Sequence. Minor sandstones occur in the marine sequences; in the Hobart region, Leaman (1976) records the Rayner Sandstone (base of the Cascades Group), Malbina Formation Member A (base of the Malbina Formation), and the Risdon Sandstone (at the base of the Ferntree Group) from the Upper Marine Sequence. These sandstone horizons are only a few metres thick, commonly feldspathic, and generally pebbly. They have not yet yielded good building sandstones, and are unlikely to do so on account of the above characteristics.

However, the Lower Freshwater Sequence is of interest as a building sandstone source, since the Nunamara sandstone (Source 25) is derived from the Liffey Group, which belongs to this sequence (Longman 1964, 1966). Since only one good quality building sandstone deposit (the Nunamara deposit) is currently known in the Lower Freshwater Sequence, it is likely that further such deposits may be rare and difficult to locate; but on the other hand the relatively good quality of the Nunamara deposit suggests that the effort required to do so may be well repaid if further such deposits can be found.

CHRONOSTRATIGRAPHIC UNITS			TASMANIAN STAGES Clarke & Farmer 1976	LITHOSTRATIGRAPHIC UNITS				ROCK TYPES	VULCANISM
				Forsyth <i>et al.</i> 1974	Clarke & Banks 1975	Forsyth, <i>in</i> Burrett & Martin 1989	Other		Banks, <i>in</i> : Burrett & Martin 1989, p. 293 - 4
TRIASSIC	UPPER	Rhaetian		UPPER		DOUGLAS RIVER BEDS UNIT 4	Volcanic lithic sandstone & coal measure sequence	(Upper Parmeener Supergroup all Terrestrial fresh-water beds)	Close & intense (intermediate, silicic, mafic)
		Norian						Lithic sandstone, coal, lutite, minor tuff, conglomerate	
		Carnian						Quartz sandstone Association	
	MID.	Ladinian				UNIT 3	Quartz and lithic sandstone sequence	Lithic sst, lutite	Close: basalt at St. Mary's, etc. (silicic + mafic)
		Anisian						Quartz sandstone	
	LOWER	(Scythian)				UNIT 2	Quartz sandstone sequence	Lutite-rich beds	Distant, mafic?
		Griesbachian						Dominantly quartz & feldspathic Qtz sandstones; minor lutites	
PERMIAN		Chhidruan ?Kazanian ?Kungurian		UPPER MARINE SEQUENCE LOWER PARMEENER SUPERGROUP	UPPER FRESH-WATER SEQUENCE	UNIT 1	Cygnat Coal Measures	Coal, sandstone, lutites	To SE, decreasing with time. Nearby, silicic
		Lymingtonian						Ferntree Formation	
		Bernacchian						Ridgdon Sandstone	
								Malbina Formation	
								Cascades Group	
								Glacio - marine beds	
								Interbedded siltstone & limestone, with minor poorly-sorted sandstones	
CARBON-IFEROUS	UPPER			LOWER MARINE SEQUENCE				Rayner Sandstone	Distant?
								Liffey Group	
								Faulkner Group	
				Tamanian				Bundella Formation	Glacio - marine beds
								Woody Island Formation	
								Tillite	
				Hellyenian				Gladgene rocks	
								tillite, rhythmites, mudstones	

TABLE 3.1 Stratigraphic relationships in the Parmeener Supergroup.

3.2.1 The Lower Freshwater Sequence

General Description

The Lower Freshwater Sequence (also termed the Lower Bernacchian non-marine interval: Clarke, *in* Burrett & Martin 1989,p.302) comprises terrestrial and minor marine deposits of sandstone, coal and lutites (mudstones and siltstones). Correlated units belonging to the Lower Freshwater Sequence include the Liffey Group, Mersey Group and Mersey Coal Measures (northern Tasmania), the Faulkner Group (Hobart area, but disappearing southwards towards Kingston), and the lower Hickman Formation (correlated marine unit in the Margate area).

An understanding of the palaeogeography and depositional environments of the Lower Freshwater Sequence is an important tool in exploration for building sandstones within the sequence (see Chapter Seven). The following description is summarised from Clarke (*in* : Burrett & Martin 1989,p.302), and Martini & Banks 1989:

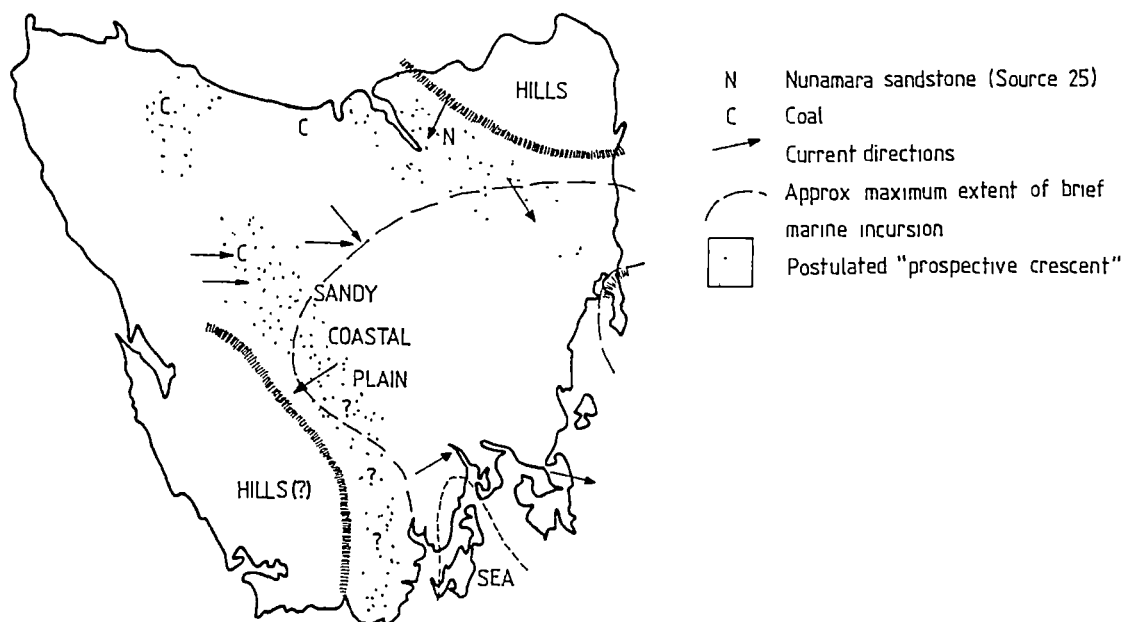


FIGURE 3.1 Palaeogeography of Tasmania during deposition of the Lower Freshwater Sequence. Adapted from Banks (*in* Spry & Banks 1962,p.202), Clarke (*in* Burrett & Martin 1989,p.302) and Martini & Banks (1989).

During the earliest Bernacchian stage (Clarke & Farmer 1976), the Lower Freshwater Sequence was deposited under post-glacial cold climate conditions (Martini & Banks 1989) in a broad fjord-like fluvial basin (the Tasmania Basin) bordered on the southwest, northwest, west and northeast by low hills from which sand and some gravel were shed. The basin opened to the sea in the southeast, with fluvial plains extending just south of Hobart at their maximum extent, and the sea being restricted to an area south of Margate (the Hickman Formation) for most of the period. The Lower Freshwater Sequence represents a regressive pulse during the predominantly marine Permian filling of the Tasmania Basin.

In general, the fluvial deposits are characterised by well sorted, quartz-rich, cross-bedded sandstone with pods of conglomerate and scattered siliceous pebbles in some places. The sandstone tends to be coarser around the margins of the basin, and finer in the southeast. Lutites become dominant in the southeast, with the Faulkner Group in the Hobart area consisting predominantly of siltstone with thin intervals of poorly sorted conglomeratic

sandstone, and the Boullanger Formation (Maria Island) consisting mainly of mudstone and sub-ordinate siltstone.

Coal was deposited, mainly in swamps around the landward margins of the basin in areas such as Latrobe, Preolenna, Mt Pelion East and St. Mary's. Lacustrine deposits were laid down in at least one lake close to the landward margin of the fluvial plain. A brief marine incursion deposited a thin marine intercalation in southeastern and central Tasmania.

The Lower Freshwater Sequence comprises a thin sheet of sedimentary rocks varying from six to fifty metres (modally 21 - 25m) thick over most of the basin. Broadly the thicknesses decrease towards the centre of the basin from the southwest, west, northwest, north and northeast, and in the centre of the basin decrease to the east and southeast.

Sedimentary facies and sandstone exploration in the Lower Freshwater Sequence

In a general way, the above information suggests that the best sandstones for building purposes (well-sorted, quartz-rich, fine to medium grained sandstones free of either significant pebbles or lutite bands) are most likely to occur in a broadly crescent-shaped band of fluvial deposits intermediate between the coastal lutite-rich southeastern part of the basin, and the coarse pebbly deposits on the landward margins of the basin towards the far northeast, central northwest and far southwest.

Martini & Banks (1989) have examined the Lower Freshwater Sequence in some detail, and have identified 22 distinct sedimentary facies, which can be grouped into marine, coastal-alluvial plain, alluvial and piedmont facies groups. Further work building upon their facies model, together with the more simplistic "prospective crescent" idea above, may prove to be a valuable tool in exploring for building-quality sandstones in the Lower Freshwater sequence.

Although several of the facies identified by Martini & Banks could conceivably include deposits of building-quality sandstone, a good place to start identifying exploration prospects is to consider the only currently known building-quality sandstone deposit in the Lower Freshwater Sequence: the Nunamara Quarry (Source 25).

Longman (1966) regarded the Liffey Group in the Launceston region, including the Nunamara deposit, as an estuarine or lacustrine deposit. However, this early model is no longer adequate in the light of Martini & Bank's work.

While the alluvial braided stream deposits identified in the Lower Freshwater Sequence by Martini & Banks are typically coarse and/or pebbly sandstones, the Nunamara deposit appears to belong to their "alluvial meandering stream deposit" (Am) facies, which they describe as:

"Am (alluvial meandering):

Well-developed sandy fining and thinning upward sequences (1-5 m thick), generally with cross-beds at the base, some massive and plane beds, capped by prevalent cross-laminations; some units may have a few basal, fine, well-rounded pebbles in thin layers, but no anomalous feature or lonestone have been found anywhere which could not be explained as formed by fluid flow; silty and sandy deposits, in places with thin coal and torbanite interlayers and plant fragments, separate the recurring sandy sequences; this facies is interpreted as bar and floodplain deposits of meandering streams." (Martini & Banks 1989,p.30)

Although the Nunamara sandstone quarry deposit does not fit the above description in every particular, the stratigraphy observed in the quarry during the present project corresponds closely in many respects (see Fig. 3.2 & Appendix One, Source 25) and probably represents essentially the same facies.

(Above the alluvial meandering stream deposit in the Nunamara Quarry there is an apparent transition to marine conditions: the alluvial sandstones are overlain by a thick grey plane-laminated mudstone similar to the coastal swale or marsh facies of Martini & Banks, and then by uniform-thickness beds of massive sandstone with a basal quartz pebble layer and rare limestones (glacial dropstones?). This latter unit appears to correspond to the marine ice zone facies of Martini & Banks, and may be the basal unit of the Bernacchian marine interval (Upper Marine Sequence), although further examination of the succession above the quarry face will be required to confirm this. See Clarke *in* Burrett & Martin 1989, p.303.)

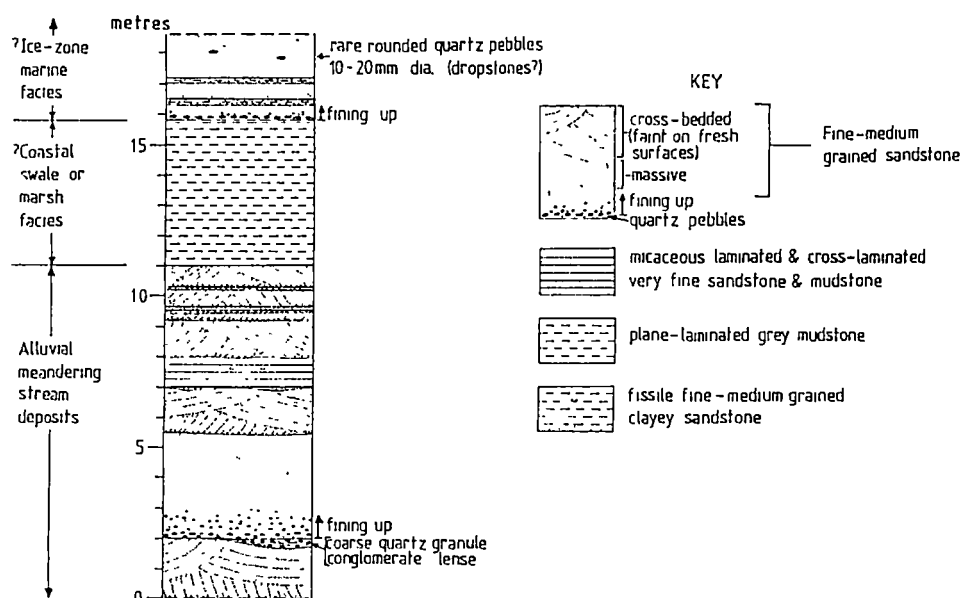


FIGURE 3.2 Stratigraphy of the Permian Nunamara Sandstone Quarry (Source 25). Lower Freshwater Sequence.

Martini & Banks recognise four regions within the Tasmania Basin, each of which contain a predominance of particular associations of their facies:

- 1) North-eastern area (includes Fingal-St. Mary's area) - Coarse gravelly alluvial fans, braided streams and meandering streams as well as some marine facies.
- 2) North and Northwestern area (includes Nunamara and Preolenna) - Sandy fluvial deposits of meandering streams and minor braided streams.
- 3) Central-north area (includes Latrobe - Interlaken area, and further south) - Sandy alluvial and coastal plains predominate. Along the N-S central axis of the basin, there is a change from primarily alluvial floodplain in the north to coastal floodplains interdigitating with near-shore deposits in the south. The northern alluvial floodplains included a few river channels, but were dominated by alluvial floodplain facies deposits ("Af" of Martini & Banks).

- 4) Southern area (Hobart-Eaglehawk area) - Primarily coastal sediments (subtidal and perhaps intertidal).

The most prospective of these four regions for fluvial meandering stream deposits, of the sort which the Nunamara sandstone appears to be, is the north and northwestern area, within which Nunamara is in fact situated. There is probably also some potential in the northeastern area, although coarse pebbly (braided stream or piedmont facies?) sandstones (such as those visited north of Mathinna (Grid Ref. EQ755173) in the Alberton quadrangle by the present writer) are common close to the landward margins of the basin, which were hilly source areas at the time of deposition.

The central-north and southern areas appear to have little potential for Nunamara-type sandstones. The alluvial floodplain and coastal plain facies of the central-north appear unprospective for building sandstones (see facies descriptions in Martini & Banks), while the Hobart area is clearly well to the southeast of the limits of the prospective areas, as the Faulkner Group rocks have been observed to be predominantly excessively fine-grained.

This distribution of prospective areas corresponds reasonably well with the concept of a "prospective crescent" as illustrated in Fig. (3.1), although it is unclear whether areas such as the southwest margins of the Tasmania Basin should be included in the "prospective crescent" as shown in Fig. (3.1). Further work could better outline the most prospective regions.

This facies model only indicates broad areas of Tasmania which may be most prospective for sandstones of the Nunamara type - it is unlikely that local occurrences of a particular facies can be predicted in detail, due to the rapid (and in practice unpredictable) lateral and vertical facies variations characteristic of fluvial deposits (see also Section 7.5.4); actual occurrences in a prospective region can only be found by detailed fieldwork.

It is possible that sandstone facies within the Lower Freshwater Sequence other than the Nunamara type may also include good building sandstones (eg, the marine "sand bar" (Sb) facies of Martini & Banks is a possibility); such facies will not necessarily be most prevalent in the same areas as the Nunamara-type sandstones.

3.3 UPPER PARMEENER SUPERGROUP SANDSTONES

The Upper Parmeener Supergroup is a thick sequence of predominantly sandy fluvial terrestrial sediments deposited in the Tasmania Basin during Late Permian to Late Triassic times.

The transition from the Lower to Upper Parmeener Supergroup varies from gradational to disconformable. There may have been Late Permian uplift and rejuvenation of source areas in northeastern Tasmania and areas west and northwest of Lake St. Clair; in any case continuing erosion and deposition caused the previously marine basin to become a terrestrial fluvial basin. The initial, upper Permian, fluvial sediments (Unit 1 below) are thin or absent in the uplifted area of northeastern Tasmania (Banks, *in* Burrett & Martin 1989, p.293).

In the Early Triassic a new cycle of fluvial quartz sandstone deposition (Unit 2 below) was initiated on a broad fluvial plain draining SSE from the Lake St. Clair region (*Ibid.*). This may in part have resulted from further uplift of the Tyennan region, although it is probable that some source areas were as far away as the west coast, or even further west (Collinson *et al.* 1987, S.Forsyth, *pers. comm.* 1990).

Regional volcanism through the Triassic (Banks, *in* Burrett & Martin 1989,p.294) may be the ultimate source of the smectite and vermiculite clays commonly found in Tasmanian Triassic sandstones (see Section 7.8.3). Volcanism in the Permian is thought to have been distant and silicic, and in the early Triassic (Unit 2 below) distant and possibly mafic. By the late Anisian (Unit 3 below) volcanism was both silicic and mafic, and was closer, with basalts being deposited at St. Mary's. Volcanism peaked in the Carnian (Unit 4 below) with mafic, intermediate and silicic pyroclastics.

3.3.1 Stratigraphy of the Upper Parmeener Supergroup

Forsyth (1987, & *in* Burrett & Martin 1989,p.309) has divided the Upper Parmeener Supergroup into four units, numbering from the base up:

Unit 1: Cygnet Coal Measures and correlates

Unit 1, which has also been referred to as the Upper Freshwater Sequence (Clarke & Banks 1975), is a sequence of generally carbonaceous sedimentary rocks and coal measures associated with sandstones and lutites, and is considered to be of Late Permian age (Forsyth, *in* Burrett & Martin 1989). Formations considered to belong to Unit 1 include the Cygnet Coal Measures, the Adventure Bay Coal Measures, the Clog Tom Sandstone and Jackey Shale, and the basal Barnetts Member of the Springs Sandstone at Hobart.

The depositional environment of Unit 1 is considered to have been a fresh-water, sandy coastal plain comprising fluvial and flood-plain systems with deltaic and lacustrine sub systems.

The sandstone beds include characteristic carbonaceous, arkosic or richly feldspathic types in southern and central Tasmania, while in northern Tasmania carbonaceous, micaceous quartz sandstone is typical (*Ibid.*). Sandstone composition varies, and includes some occurrences of quartz sandstone, especially near the top of the sequence in southern Tasmania.

Sandstone of Unit 1 is distinguished from the overlying Triassic quartz sandstone by generally thinner and less massive bedding, a generally feldspathic & carbonaceous composition, and by the presence of clayey or calcareous cement or matrix which has reduced the tendency for development of the glistening quartz grain overgrowths (quartz cement) characteristic of the Triassic sandstones (*Ibid.*). All these characteristics make the Unit 1 sandstones less prospective as building stone.

Good outcrops of Unit 1 sandstone were examined during this project at Stonor, Crichton Rd., and Baden, south of Oatlands. The strength, porosity, joint spacing and bedding thicknesses are acceptable, but the stone contains significant smectite swelling clay and feldspar, and is of an unattractive banded yellow-grey appearance.

Although it is conceivable that beds of building-quality sandstone could occur in Unit 1 deposits, the general characteristics of the sandstone are such as to make the unit a prospect of low potential.

Unit 2: Quartz Sandstone Sequence

This unit, which is of Early Triassic age, contains all the building sandstone quarries of reasonable to good quality which have been opened in Triassic-age sandstones in Tasmania. The Quartz Sandstone Sequence is dominated by well-sorted medium to fine grained quartz

sandstones. Cross-bedded and massively-bedded horizons are common. The unit remains the best prospect for high quality sandstone in the Triassic sequences of Tasmania and is discussed in Section (3.3.2) below.

Unit 3: Quartz and Lithic Sandstone Sequence

Forsyth (*in* Burrett & Martin 1989) identifies Unit 3 as a sequence of quartz sandstones, lithic sandstones, lutites and coal of middle Triassic (Pre-Anisian? to Ladinian) separating the Lower Triassic Quartz Sandstone Sequence from the Upper Triassic Lithic Sandstone Sequence.

Unit 3 occurs in the Midlands of Tasmania and in surrounding regions (*Ibid.* Fig. 8.12c). In some regions Unit 3 is missing, the interval being marked by a hiatus, while in other areas such as near St. Mary's and Apslawn, Unit 3 quartz sandstones form the base of the Triassic sandstones, overlying a hiatus spanning the Lower Triassic.

Unit 3 comprises a basal quartz sandstone interval, a middle interval with lithic sandstone and lutite, and an upper interval known as the quartz sandstone association, comprising sandstones and lutites (*Ibid.*). This entire sequence is not always present.

The basal quartz sandstone interval comprises coarse granule sandstone, and lenticular quartz sandstone beds interbedded with lithic sandstone and lutites (*Ibid.*). Although some of the quartz sandstone beds could conceivably be prospective for building sandstone, the high lutite and lithic sandstone content of the interval suggests a low prospectivity in general.

The middle interval of Unit 3 comprises lithic sandstone and abundant lutite (*Ibid.*). Lithic sandstone is not suitable for building purposes due to its content of felsic and other grains susceptible to alteration to clays.

The upper quartz sandstone association shows considerable variation, but is typically a clean white quartz sandstone associated with lutites and some coal seams. The sandstone composition varies laterally from quartzose to lithic or feldspathic. Sandstone- and lutite-dominated intervals occur in about equal proportions, and lutite is commonly interbedded to interlaminated with sandstone. Triassic basalts near St. Mary's are contemporaneous with the quartz sandstones. (*Ibid.*)

Again, it is conceivable that building-quality sandstone could occur in the upper quartz sandstone association, but the high lutite content and the presence of lithic and feldspathic compositions gives the association low prospectivity.

In the Hobart and Brighton quadrangles, parts of the lithological association mapped by Leaman (1972) and Leaman *et al.* (1975) as "Rlm" (Assemblage 5 of Leaman 1976, 1977) belong to Unit 3 (Forsyth, *in* Burrett & Martin 1989, p.325). Leaman's "Rlm" comprises predominantly thinly bedded mudstone, minor quartz sandstone, lithic sandstone and minor coal.

Unit 4: Volcanic Lithic Sandstone and Coal Measure Sequence

This unit, which is of upper Triassic (Carnian) age, is widespread over much of the Tasmania Basin, and consists predominantly of volcanic lithic sandstone, lutite, coal, and rare tuff and conglomerate beds (Forsyth, *in* Burrett & Martin, 1989).

Where lithic sandstones from Unit 4 have been used in the past for building purposes (eg,

Ouse Source 19, buildings in the Hamilton area, a road bridge at Jericho), they have often performed very poorly. The Ouse Church of England, for instance, experienced very deep cracking in lithic sandstone masonry, probably as a result of swelling clays in the stone (see Plate 5.3).

The high proportion of feldspars and ferro-magnesian minerals present in lithic sandstones containing volcanic grains may partially alter to produce a high content of clays, including smectite swelling clay (see Section 7.8.3). For this reason alone, lithic sandstones are considered unsuitable as building sandstones, so that Unit 4 is regarded as unprospective.

3.3.2 The Quartz Sandstone Sequence (Unit 2)

The Early Triassic (Griesbachian - Pre-Anisian?) Quartz Sandstone Sequence outcrops widely throughout the Tasmania Basin of central, northern and southeastern Tasmania, reaching stratigraphic thicknesses of up to 280 metres (Forsyth, Fig 8.12b, *in* Burrett & Martin 1989). Broadly, the sequence contains well sorted, commonly cross-bedded quartz sandstone with abundant quartz grain overgrowths, feldspathic quartz sandstone, and coloured lutites (Forsyth, *in* Burrett & Martin 1989).

Mineralogic determinations by Eggert (1983, quoted by Forsyth (*Ibid.*) with non-Unit 2 data removed) gave the following ranges of grain compositions for sandstones in the Quartz Sandstone Sequence:

Quartz:	45 - 100% (av. $84 \pm 10\%$)
Feldspar:	0 - 47% (av. $11 \pm 8\%$)
Lithic grains:	0 - 18% (av. $5 \pm 3\%$)

Eggert found a low plagioclase to total-feldspar ratio (0.34), and the volcanic proportion of the lithic grains was also low (0.31).

Clay minerals present include illite, kaolinite, smectite (montmorillonite), mixed layer

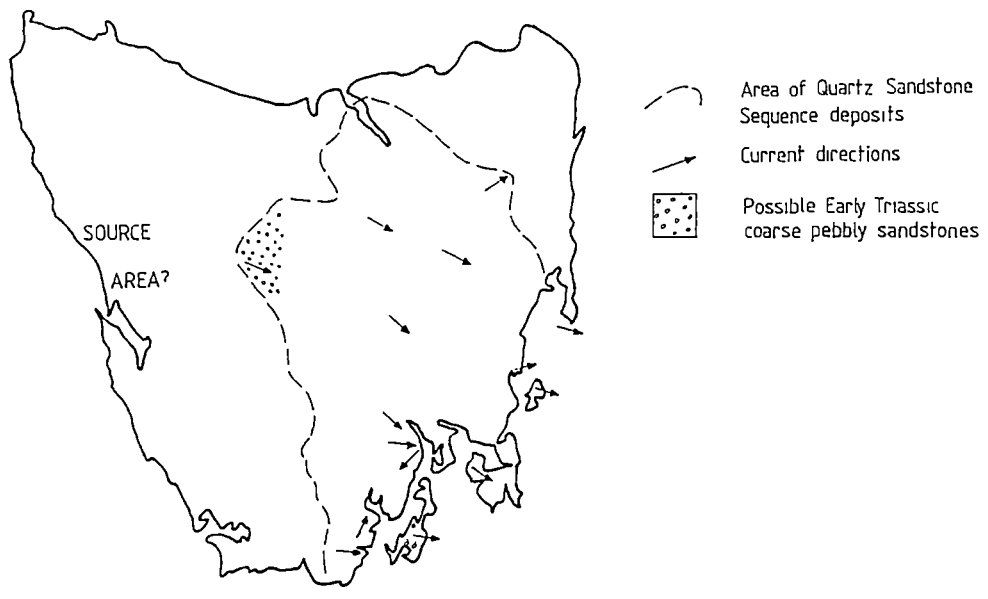


FIGURE 3.3 Distribution and palaeogeography of the Early Triassic Quartz Sandstone Sequence. Adapted from Forsyth (Fig. 8.12b, *in* Burrett & Martin, 1989).

illite/smectite and vermiculite. Chlorite is less common, and halloysite was identified in the Cobbs Hill Quarry (Source 23) during this study. Mica and graphite may be locally abundant in the sandstones.

The Quartz Sandstone Sequence tends to fine upwards from medium- and coarse-grained at the base to fine- and very fine-grained sandstones, and to lutites at the top (Leaman 1976 & 1977, Forsyth 1984 and *in* Burrett & Martin 1989). In some areas the proportion of lutite, mica and feldspar tends to progressively increase up the sequence (Leaman (1976, 1977) found these trends in the Hobart and Brighton quadrangles). In borecore from near the top of the sequence, feldspar and lithic grains are more common, and quartz content falls below 70%(Forsyth, *in* Burrett & Martin 1989). However, basal beds in the Midlands and at Poatina may be more feldspathic than higher beds, and, apart from the recognition of an upper lutite-dominated interval (see below), sub-divisions of the sequence based on variation in lutite content are only locally applicable (*Ibid.*).

Quartz pebbles are common only in the basal few metres of the sequence, and are rare higher up (Forsyth 1987). Palaeo-current directions indicate derivation of sediments from the west or north west (see Fig. 3.3 & Collinson *et al.* 1987), and pebbly beds are probably more common upstream, where such beds, which may correlate with Unit 2, are notable in the Lake St. Clair region (Forsyth, *in* Burrett & Martin 1989). Pebbly beds are also common in the Quartz Sandstone Sequence on Bruny Island (S.Forsyth *pers. comm.* 1990).

Forsyth (*in* Burrett & Martin 1989) divides the Quartz Sandstone Sequence on a regional scale into a thick (approx. 200m) lower dominantly sandstone interval, and a thin (20 - 60m) upper predominantly lutite interval. In the Hobart region the dominantly sandstone interval is represented by parts of the Springs Sandstone (Banks & Naqvi 1967) and the Knocklofty Formation (Camp & Banks 1978). In the Hobart/Brighton/Rhyndaston area, the rock sequences mapped by Leaman (1972) and Leaman *et al.* (1975) as Rls and Rlq

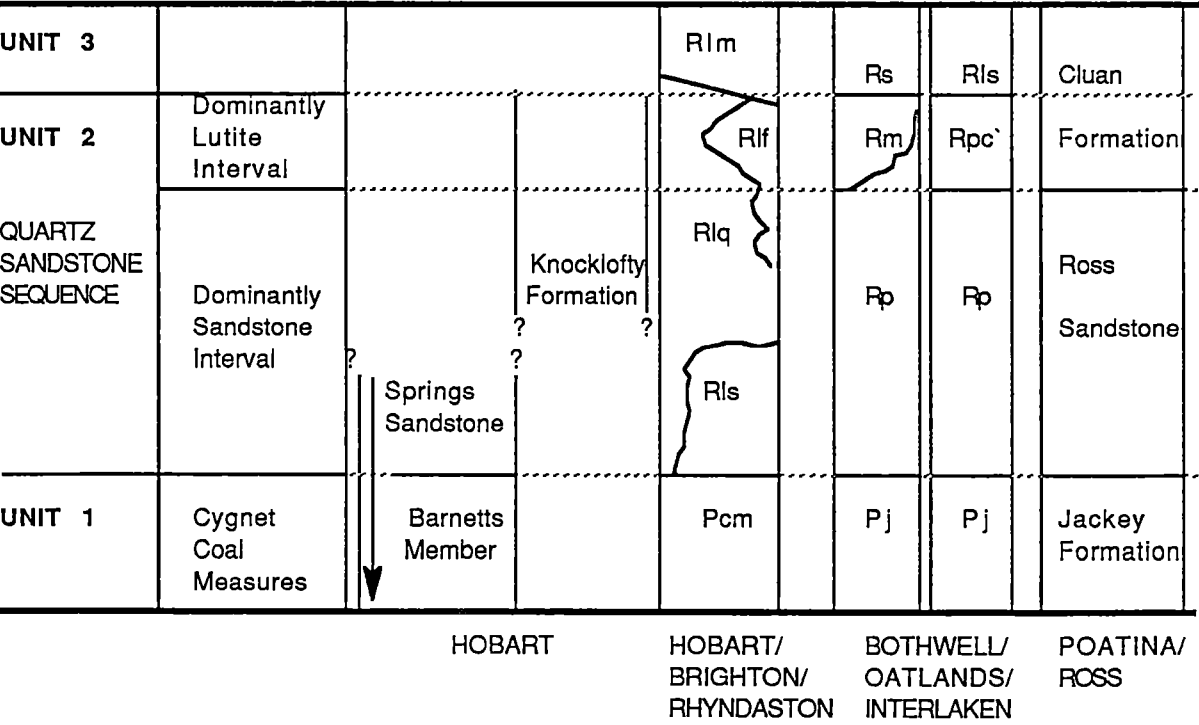


TABLE 3.2 Correlation of some mapped units corresponding to the Quartz Sandstone Sequence (see text).

correspond to the dominantly sandstone interval, as does rock sequence Rp in the Oatlands/Bothwell/Interlaken area (Forsyth *et al.* 1976, Forsyth 1984, 1986, 1989) and the Ross Sandstone of the Poatina area (McKellar 1957). These stratigraphic relationships are indicated in Table (3.2). (See Forsyth 1987 for more detailed correlation charts).

Within the dominantly sandstone interval, lutites (claystone, mudstone), in the form of isolated lenticular beds, thicker variable intervals and clay pellets within sandstone beds, appear in most regions to be distributed in a more or less random fashion (Forsyth, *in* Burrett & Martin 1989). However, as noted above, in some areas a general upwards increase in lutite content has been recorded.

Thick intervals (60-80m) in the dominantly sandstone interval consist entirely of sandstone formed by cycles of fluvial deposition. Forsyth (1984, & *in* Burrett & Martin 1989,p.317) describes typical cycles as being characterised by a fining up sequence grading from medium to coarse sandstone at the base to medium-fine grained and rarely muddy rocks higher up. The basal beds typically overlie an erosional scour surface and may be massive, tabular or festoon cross-bedded. If present, clay-pellet bands or rarely quartz pebbles are most common at the base of cycles. Low angle cross-bedding occurs both high and low in cycles, and fine planar laminations and ripple cross-laminations occur high.

The Quartz Sandstone Sequence is considered to have been deposited by low sinuosity rivers flowing towards the east or southeast from source areas to the west and northwest (Forsyth, *in* Burrett & Martin, 1989). Collinson *et al.* (1987) consider the Quartz Sandstone Sequence to have been deposited in a braided (rather than meandering) stream system, with migrating channel, bar and sandflat environments. The quartz sandstone beds constitute channel, braid (and minor point?) bar deposits, while the lutites represent cut-off channel, lacustrine and over-bank deposits.

The relative lack of lutites in the lower predominantly sandstone interval is attributed to frequent reworking of over-bank deposits due to channel migration across the floodplain (*ibid.*). However, as river size decreased with development of the basin, such reworking would have become less frequent so that the proportion of lutites preserved increased. In some areas this trend is evident in an general upwards increase in lutite content, but it is most marked by the regional occurrence of the upper predominantly lutite interval.

Sandstone exploration in the Quartz Sandstone Sequence

In contrast to the Permian Lower Freshwater Sequence, current knowledge of the palaeogeography and palaeoenvironments of the Quartz Sandstone Sequence depositional basin allows little discrimination to be made between geographical regions in which sedimentary facies associations more and less favourable for production of building quality sandstones may occur.

One exception to this is that the region of coarse pebbly (piedmont?) possible Unit 2 sandstones in the west, which were deposited close to source areas west of Lake St. Clair, are clearly unsuitable, as are similar pebbly beds on Bruny Island.

At the other extreme, basic sedimentological principles would predict decreasing grainsize and bedding thickness, and an increase in lutite content, going laterally southeast (downstream) from the source area. While such trends may in fact occur (insufficient data is available to tell), well-sorted and fine-medium grained sandstones of adequate bedding thickness are still found in the Port Arthur area, which is the extreme south-eastern (distal) part of the basin exposed above sea level today.

Thus, any such lateral trends which may occur in the sandstone dominated interval of the Quartz Sandstone Sequence do not appear to be significant enough to completely eliminate any particular geographical areas from consideration as building sandstone prospects. The lack of a marked regional gradient in grainsize, bedding thickness and lutite content in the Quartz Sandstone Sequence suggests that the Tasmania Basin as it exists today is only part of an originally much larger depositional basin (S.Forsyth *pers. comm.* 1990)

Therefore, apart from the western margins of the basin, clean fluvial channel and braid bar deposits comprising well-sorted, fine-medium grainsize sandstones of adequate bedding thickness are found throughout the area of deposition indicated in Fig. (3.3). Many of these may be prospective for building sandstone, subject to other criteria discussed elsewhere in this work.

However, in contrast to the relative lack of significant lateral variability, there is sufficient vertical stratigraphic variability in the Quartz Sandstone Sequence to indicate that certain horizons may be more prospective than others.

Most obviously, the upper lutite dominated interval is of low prospectivity. The lower sandstone dominated interval of the Quartz Sandstone Sequence is thus of the greatest interest. With regard to this interval, several broad trends in the sequence (see above) are noted which may be important:

Although not ubiquitous trends, an increase in the proportion of feldspar, mica and lithic grains occurs going up through the sequence in some areas, while quartz content may conversely decrease. These trends imply sandstones of a more stable and thus durable mineralogy will tend to be more prevalent lower in the sequence.

Grainsize broadly decreases going up through the sequence, and in some (but not all) areas lutite content increases upwards through the dominantly sandstone interval. Since fine-medium grain sizes are desirable for building sandstones, the coarsest and most pebbly sandstones in the basal few metres of the sequence are likely to be unsuitable. Above this however, the lower parts of the dominantly sandstone interval are likely to be the most prospective, since excessively fine-grained sandstones and lutites broadly become more prevalent high up. Additionally, the generally finer grain sizes higher in the sequence imply thinner (and thus less suitable) bedding towards the top (see Section 7.5.2).

In summary, it appears likely that the entirety of the lower dominantly sandstone interval of the Quartz Sandstone Sequence is prospective for building sandstone, although such broad vertical (stratigraphic) trends as are apparent in at least some areas suggest that the highest potential for high quality building sandstones occurs in the lower parts of that interval, excluding the basal few metres.

Prospective formations and rock units correlated with the lower dominantly sandstone interval in various parts of Tasmania are indicated in Table (3.2), and include the Knocklofty Formation and upper part of the Springs Sandstone at Hobart (but see further discussion below), the Ross Sandstone in the Poatina-Ross area, the rock sequence "Rp" in the Bothwell - Oatlands - Interlaken region, as well as at least the lower part of "Rs" in the Kingborough quadrangle (Farmer 1981), and "Rs" or "Rss" in the Sorell quadrangle (Gulline 1982).

In mapping the Hobart and Brighton quadrangles, Leaman (1972) and Leaman *et al.* 1975 did not attempt to correlate the Quartz Sandstone Sequence with the Knocklofty Formation or

the Springs Sandstone, but instead subdivided the sequence according to lithological associations which have proven to be useful in building sandstone exploration.

Although Leaman's associations were mapped on a purely lithological basis, in many areas they fall into a stratigraphic sequence as indicated in Table (3.3) below (see also Table 3.2).

It is noteworthy that existing quarries only occur within RIq and RIs, and that the best quality stone quarries of those (eg, Linden, Cobbs Hill) occur within RIs.

Lithological Association	Description	Existing quarries within association
TOP		
Rlf	Dominantly thinly bedded medium-fine quartz sandstone, minor mudstone; micaceous, graphitic and feldspathic. (minor occurrence)	-
RI		
RIq	Dominantly medium-coarse quartz sandstone with minor mudstone, minor mica and minor feldspar. May exceed 150m thickness.	Tea Tree, Campania, Lindisfarne, Gordon's Hill, Kangaroo Point White.
RIs	Thickly bedded medium-coarse quartz sandstone with very minor lutites. Thickness 15 - 120m.	Linden, Elderslie, Cobbs Hill, Pontville, Waterworks, Risdon, Lachlan, Molesworth, Kingston, Kangaroo Point Green.
BASE		

TABLE 3.3 Mapped units correlated with the Quartz Sandstone Sequence in the Hobart and Brighton Quadrangles.

Lithological association Rlf is of limited lateral extent, and its thinly bedded micaceous, feldspathic and graphitic nature indicates that it is unlikely to be prospective for building sandstones. It may be equivalent to the lower part of the predominantly lutite upper interval, and to some lower horizons, of the Quartz Sandstone Sequence (S.Forsyth *pers. comm.* 1990).

The associations RIs and RIq correspond to the dominantly sandstone interval of the Quartz Sandstone Association. In many areas, RIs lies stratigraphically below RIq. Association RIs contains a higher proportion of thickly bedded sandstone, has a lower lutite content and appears to be less micaceous or feldspathic than RIq. This supports the assertion made above that in some areas (specifically the Hobart and Brighton quadrangles in this case) the lower parts of the dominantly sandstone interval of the Quartz Sandstone Sequence have the greatest prospectivity for good building sandstone.

S. Forsyth (*pers. comm.* 1990) suggests that RIs and RIq may in some areas occur interbedded or grading laterally into each other. RIs probably represents higher-energy channel deposits which, whilst having been more widespread during the older (earliest) phases of deposition of the Quartz Sandstone Sequence, can nonetheless be found intermittently at horizons of younger age.

Thus, although associations Rls and Rlq both appear to be prospective, Rls appears to be more prospective for good building sandstones than Rlq. This assessment is supported by the greater number of good building stone quarries which have actually been developed in the Rls association.

CHAPTER FOUR

TASMANIAN BUILDING SANDSTONE SOURCES: SUMMARY OF DATA

4.1 INTRODUCTION

This chapter gives a brief overview of the important Tasmanian sandstone quarries. All currently operating quarries are included, as well as the important historical ones. However a number of minor quarries are not included here (eg, Sarah Island Cambrian greywacke quarries, Ouse lithic sandstone quarry, minor Quartz Sandstone Sequence quarries). Full details of all quarries examined during this project (both major and minor) are given in Appendix One.

In the following listings, quarries are grouped according to current working status (current or disused), general aesthetic character (grey/white, brown or strongly banded), and stone type obtainable (large dimension blocks or flagstone).

Certain laboratory data (porosity, strength, etc) is only given for currently working quarries, since in many cases the samples from disused quarries which were tested were weathered and thus are likely to have yielded unreliable laboratory results.

All the quarries listed below occur within the Early Triassic Quartz Sandstone Sequence (Forsyth 1987), apart from the Nunamara Quarry which belongs to the Permian Lower Freshwater Sequence. Grain size and sorting are not listed, since all these quarries contain fine- to medium-grained, moderately well to well sorted sandstones.

Bedding types listed refer to the quarry product; other bedding types occur in some quarries, but have not been used for building purposes.

Relative abundances of clay types in the matrix of each sandstone type are classified as:

D	Dominant
CD	Co-dominant
SD	Sub-dominant
M	Minor
T	Trace

The location of the quarries are shown on Figures (4.1) and (4.2).

4.2 MAJOR DISUSED QUARRIES

Uniform grey/white bulk colouration (ferruginous banding absent or minor)

Large dimension blocks obtainable

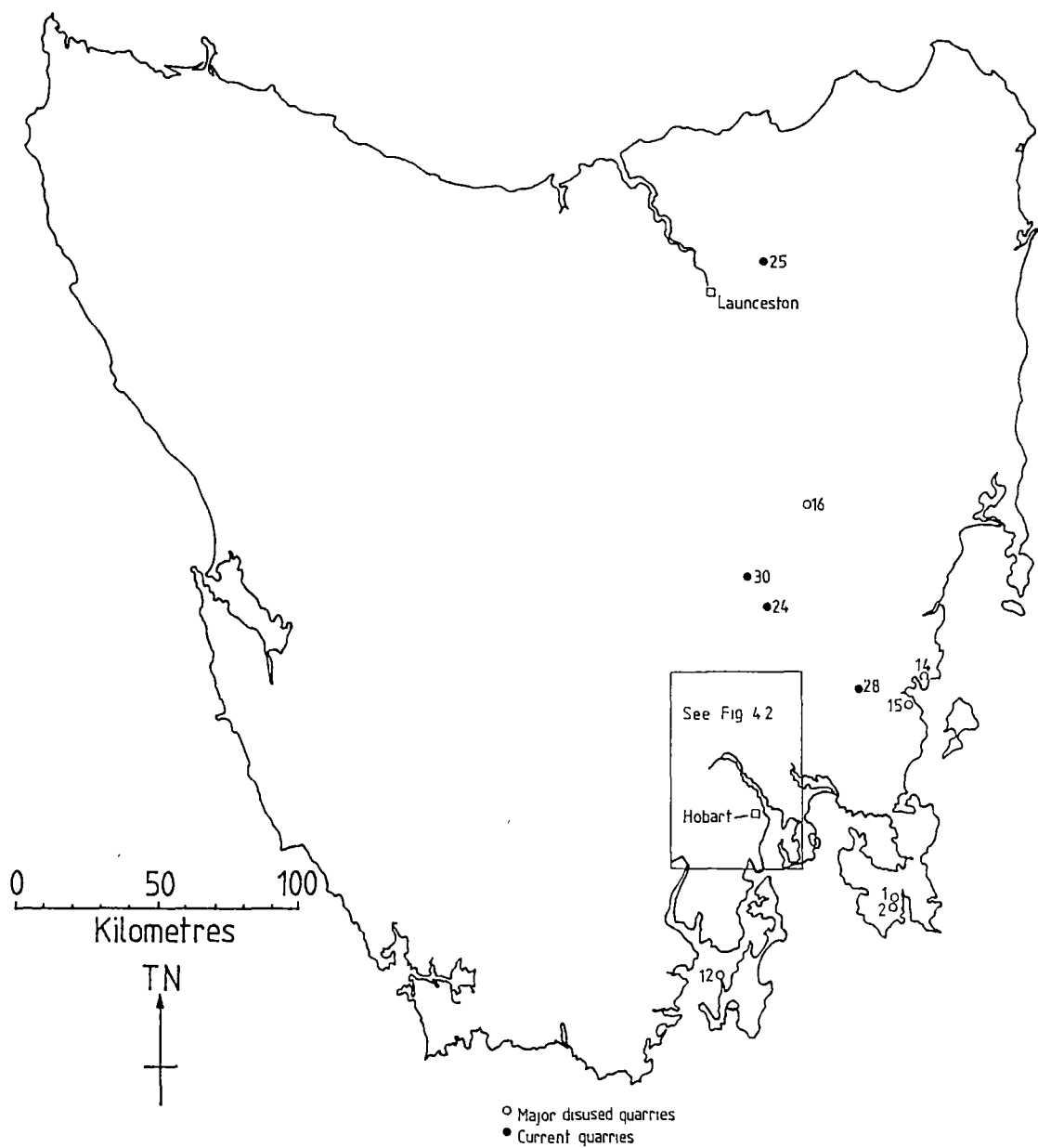
Quarry [Source No.]	Colour patterning	Bedding	Joint spacings(m)	Clay types present	Other features
Kangaroo Pt. Green [4] Plates (5.4) & (5.5)	Light grey/ green bulk colour, minor liesegang rings.	Massive/ faintly cross- bedded	0.1 - 1.5	Smectite (D) Illite (SD) Kaolinite (SD) Chlorite (M)	Minor clay pellets quartz pebbles & vertebrate fossils
Kangaroo Pt. White [5]	minor brown ferruginous staining	Massive & Cross-bedded	2.0 - 3.0	Smectite (M) Illite (SD) Kaolinite(D)	Minor clay pellets
Ventenat Pt. [12]	Uniform colour	Massive & Cross-bedded	3.0	Smectite (M) Illite (M) Kaolinite (D)	Rare clay pellets
Tea-Tree [13]	Uniform colour	Cross-bedded	<10.0	Smectite (M) Illite (CD) Kaolinite (CD)	Clay pellets are common; deep random fractures a problem
Orford [15]	Minor brown liesegang rings and mottles	Cross-bedded	1.0 - 6.0	Illite (SD) Kaolinite (D)	Minor clay pellets (in bands)
Ross [16] (some quarries)	Uniform colour	Cross-bedded	2.0+	Illite (CD) Kaolinite (CD)	Some Ross quarries have strong brown liesegang rings.

Uniform brown bulk colouration (ferruginous banding absent or minor)Large dimension blocks obtainable

Quarry [Source No.]	Colour patterning	Bedding	Joint spacings(m)	Clay types present	Other features
Plummers (Pt. Arthur) [1]	Uniform colour	Planar (thick)	-	Smectite (D) Illite (SD)	Minor clay pellets
Palmers (Pt. Arthur) [2]	Uniform colour	Cross-bedded	2.0	Smectite (CD) Illite (CD)	Major salt attack in quarry
Domain [7] Plate (7.9)	Minor brown liesegang rings and mottles	Massive/ cross-bedded	-	Smectite (SD) Illite (D) Kaolinite (SD)	Characteristic pale "stringers" and porous spots. Minor clay pellets
Knocklofty [8]	Minor brown liesegang rings and stains	Massive/ cross-bedded	-	Smectite (M) Illite (M) Kaolinite (D)	Large quarry; variable stone
Waterworks [9]	Brown nodules in parts	Massive/ cross-bedded	<2.0	Illite (D) (other quarries different?)	Several quarries; also include grey/ white stone.
Lindisfarne [11]	Distinctive pink/brown uniform bulk colour	Cross-bedded	-	-	

Strong ferruginous bandingLarge dimension blocks obtainable

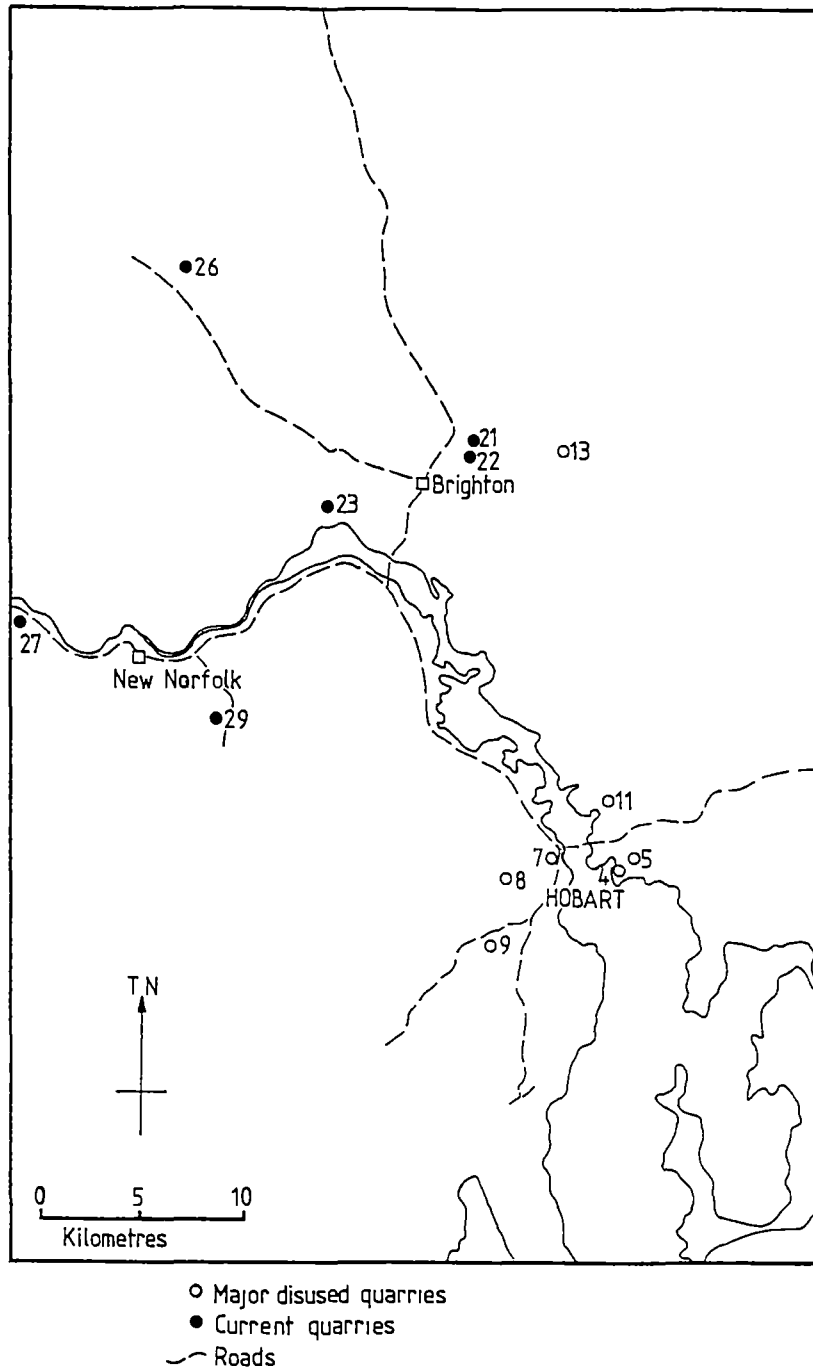
Quarry [Source No.]	Colour patterning	Bedding	Joint spacings(m)	Clay types present	Other features
Okehampton [14]	Grey/white bulk colour with strong liesegang rings	Massive/ cross-bedded	<1.0-2.0+	Illite (T) Kaolinite (D)	Minor clay pellets & quartz pebbles in upper parts.
Ross [16] (Some quarries)	Grey/white bulk colour with strong liesegang rings	Massive/ cross-bedded	2.0+	Illite (CD) Kaolinite (CD)	Some Ross quarries have uniform grey/ white colouration.



Key to numbered quarries (Source numbers as per Appendix One)

- | | |
|------------------------|---------------------|
| 1 Plummers | 16 Ross |
| 2 Palmers Lookout Road | 24 Oatlands |
| 12 Ventenat Point | 25 Nunamara |
| 14 Okehampton | 28 Buckland |
| 15 Orford | 30 Mike Howes Marsh |

Figure 4.1 Tasmania: Major sandstone quarries locality map



Key to numbered quarries (Source numbers as per Appendix One)

4 Kangaroo Point Green	21 Pontville Brown
5 Kangaroo Point White	22 Pontville White
7 Domain	23 Cobbs Hill
8 Knocklofty	26 Elderslie
9 Waterworks	27 Linden
11 Lindisfarne	29 Molesworth
13 Tea Tree	

Figure 4.2 Hobart area: Major sandstone quarries locality map

4.3 CURRENT QUARRIES (some also used historically)

Uniform grey/white bulk colouration (ferruginous banding absent or minor)

Large dimension blocks obtainable

Quarry [Source No.]	Colour patterning	Bedding	Joint spacings(m)	Clay types present	Other features
Pontville White [22] Plate (4.1)	Uniform colour	Massive	1.0 - 3.0	Smectite (T) Illite (D) Kaolinite (SD)	Porous spots abundant.
Nunamara [25] Plate (4.3)	Brown liesegang rings in parts only.	Massive/ cross-bedded	1.0 - 4.0	Illite (SD) Kaolinite (D) Vermiculite (M)	Liesegang rings only within 1.0 - 1.5m of joints.
Buckland [28] (parts of quarry) Plate (4.4)	Uniform colour	Cross-bedded	10 - 30	Illite (SD) Kaolinite (D)	Strong round patches common

Uniform brown bulk colouration (ferruginous banding absent or minor)

Large dimension blocks obtainable

Quarry [Source No.]	Colour patterning	Bedding	Joint spacings(m)	Clay types present	Other features
Cobbs Hill [23] Plate (4.5)	Brown nodules common	Massive	<1.0	Smectite (T) Illite (SD) Kaolinite (D) Halloysite (T)	
Oatlands [24] Plate (4.6)	Uniform colour	Massive	3.0 - 7.0	Smectite (T) Illite (CD) Kaolinite (T) Vermiculite (CD)	Small black spots common
Elderslie [26] Plates (4.7), (5.7) & (7.2)	Uniform colour	Massive	5.0 - 15.0+	Illite (SD) Kaolinite (M) Vermiculite (D)	Black and pale green spots & patches.
Linden [27] Plates (4.8) & (5.6)	Subdued brown liesegang rings	Massive	<0.5 - 4.0	Smectite (M) Illite (CD) Kaolinite (CD) Chlorite (T)	Clay pellets in lower part of massive bed.

Strong ferruginous bandingLarge dimension blocks obtainable

Quarry [Source No.]	Colour patterning	Bedding	Joint spacings(m)	Clay types present	Other features
Pontville Brown [21] Plate (4.2)	Grey/white bulk colour with strong ferruginous patterns.	Massive/ Cross-bedded	<0.5->2.0	Smectite (T) Illite (D) Kaolinite (M)	Porous spots common.
Buckland [28] (parts of quarry) Plate (4.9)	Grey/white bulk colour with strong liesegang rings	Cross-bedded	10 - 30	Illite (SD) Kaolinite (D)	Strong round patches common

Flagstone slabs obtainable

Quarry [Source No.]	Colour patterning	Bedding	Joint spacings(m)	Clay types present	Other features
Molesworth [29] Plates (4.10) & (7.7)	Grey/white bulk colour with strong liesegang rings	Planar	1.0 - 3.0	Illite (CD) Kaolinite (CD)	
Mike Howes Marsh [30] Plate (4.11)	Grey/white bulk colour with strong liesegang rings	Planar	1.0 - 5.0	Illite (SD) Kaolinite (D)	

Quarry [sample]	Effective Porosity (Vol. %)	Dry Bulk Rock Density (t/m ³)	Dry Point Load Strength Index (Av. all directions, MPa)	Ultrasonic Pulse Velocity (Av. all directions, m/sec)	Clay Matrix (Vol. %)
Pontville Brown [Etna 1]	10.76	2.13	1.18	2704	18
Pontville White [Etna 3]	12.06	2.11	0.80	2629	15
Cobbs Hill [C/1/1]	9.74	2.12	6.23 (anomalous?)	-	10
Oatlands [Riz 1]	16.35	2.17	0.90	2223	24
Nunamara [N1]	10.66	2.39	1.19	2338	25
Elderslie [51/2/6]	11.65	2.34	2.01	-	15 - 20
Linden [L2]	11.83	2.29	1.11	2575	13
Buckland White [67/1/4]	9.63	1.96	1.37	-	17
Buckland Brown [67/1/1]	13.63	1.99	1.25	-	32
Molesworth [FB 1]	8.97	2.17	2.11	3262	23
Mike Howes Marsh [MH 1]	10.15	2.27	2.46	3032	23

TABLE 4.1 Current Quarries: technical data on representative samples.



Plate 4.1 Pontville White sandstone (Source 22).



Plate 4.2 Pontville Brown sandstone (Source 21).



Plate 4.3 Nunamara sandstone (Source 25): Entrance restoration, Old St. Mary's Hospital, corner of Davey St. and Salamanca Place, Hobart (1982 - 83). Original stone surrounding is Kangaroo Point Green Sandstone (Source 4).



Plate 4.4 Buckland Quarry white sandstone (Source 28).



Plate 4.5 Cobbs Hill Quarry sandstone (Source 23). Note ferruginous concretions and pale streak (common features in this source).



Plate 4.6 Oatlands Quarry sandstone (Source 24), used (1988) on Hobart Stock Exchange, 85 Macquarie St.



Plate 4.7 Elderslie Quarry sandstone (Source 26), used (1989) in portico restoration, Old Supreme Court (corner of Macquarie and Murray St.s, Hobart); Massive sandstone above, cross-bedded stone below.

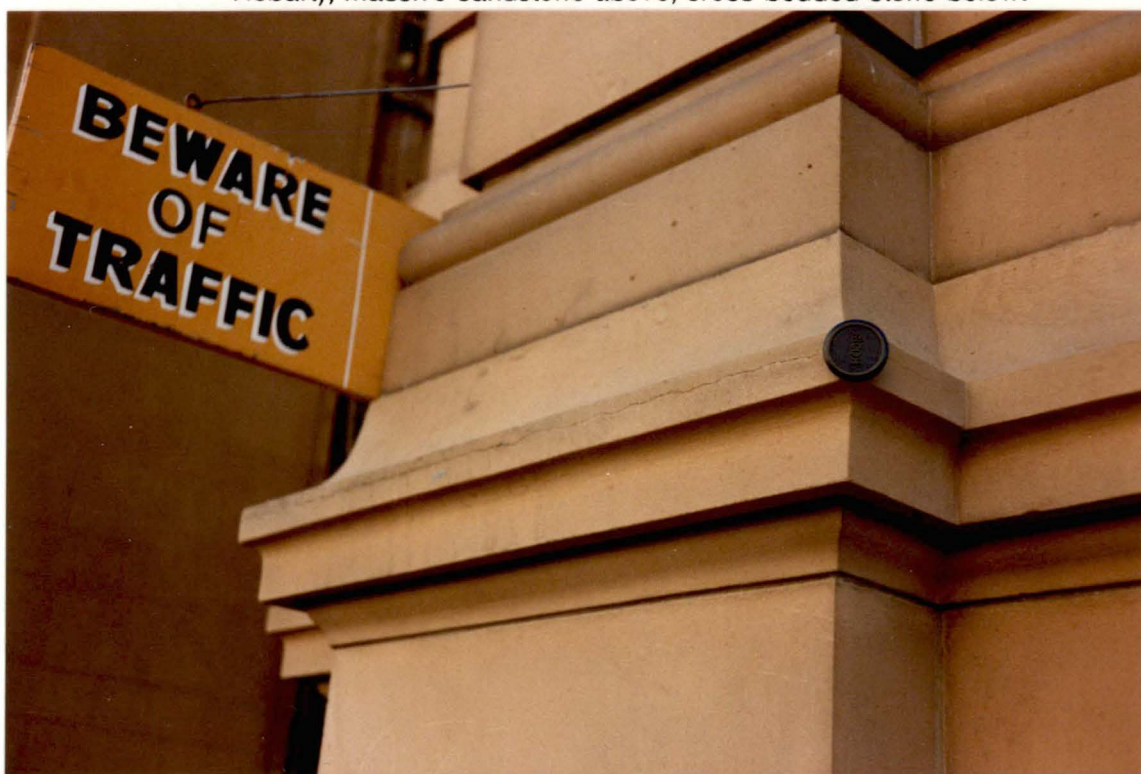


Plate 4.8 Linden Quarry sandstone (Source 27), used (1901) in Hobart G.P.O.; note generally excellent condition, except for cracking under ledge which is typical of smectite-bearing sandstones.



Plate 4.9 Buckland Quarry "striped" sandstone (Source 28). Note effect of circular patches upon Liesegang ring morphology.



Plate 4.10 Molesworth Quarry sandstone (Source 29). Typical flagging slabs.



Plate 4.11 Mike Howes Marsh Quarry (Source 30). Note strong lieegang rings and distinct planar bedding, which forms flagging slabs inter-laminated with thin clayey laminations allowing easy removal of the slabs.

CHAPTER FIVE

DECAY PROCESSES IN SANDSTONE BUILDINGS

5.1 INTRODUCTION

In order to determine how best to test and evaluate the durability of sandstone, it is necessary to examine the processes by which sandstone decay occurs. The purpose of this chapter is to review sandstone decay processes, leading to determination of the way in which sandstone properties control the resistance or susceptibility of the stone to those decay processes.

It was not an aim of this project to determine the processes causing sandstone decay, as much work has already been done on this problem by others. This chapter therefore contains simply a brief resumé of existing information on decay processes, with particular reference to Tasmanian conditions.

5.2 SANDSTONE DECAY PROCESSES

Spry (1981) provides the following list of processes which can give rise to decay and failure of sandstone in buildings. The separation of processes into these categories is a little artificial, since many modes of decay involve the effects of more than one of these categories.

(A) MECHANICAL WEATHERING

- (i) Crystal growth - e.g. salt crystal growth in pores.
- (ii) Frost action - frost wedging, water freezing and expanding in pores.
- (iii) Thermal Stress Failure - crumbling, cracking, warping due to hot/cold cycles giving expansion/contraction of stone. This can have a dis-proportionate effect on salt grains in pore spaces, increasing the aggressiveness of any salt attack process which may be taking place.
- (iv) Abrasion - due to airborne particles, feet on pavements or steps, etc.
- (v) Impact - mechanical collisions.
- (vi) Vibration - fatigue due to traffic or mechanical plant works.
- (vii) Structural failure - failure of buildings rather than materials - due to ground subsidence, poor design, etc.
- (viii) Mineral expansion - swelling clays, salt hydration, etc.

(B) CHEMICAL WEATHERING

- (i) Hydration and hydrolysis - addition of water to minerals, causing chemical reactions (eg, breakdown of feldspar to form clay).
- (ii) Solution - leaching of soluble compounds, eg, calcite. Leaching of feldspars, micas

and clays, leading to mineralogical changes.

- (iii) Acid attack - formation and action of dilute carbonic, sulphurous, sulphuric, nitric, humic, etc, acids.
- (iv) Oxidation - eg, formation of iron oxides. May not necessarily lead to weakening of stone, and can increase attractiveness of the stone.

(C) PHYSICO/CHEMICAL WEATHERING

- (i) Organic processes - eg, lichen and moss growth, bird droppings, micro-organisms.
- (ii) Mineral expansion - eg, swelling clays, salt growth and hydration.

5.3 MODES OF SANDSTONE DECAY IN BUILDINGS

Of these weathering processes, a number are usually of only minor importance in Tasmania. Frost action and thermal stress failure do not appear to be processes significantly affecting Tasmanian sandstones; even in midland areas such as Ross and Oatlands, which often suffer frosts, the sandstone buildings show little apparent frost damage.

The following sections discuss particular modes of decay; some of these encompass several of the decay process categories listed above. Of these processes, salt attack and cyclic expansion and contraction of swelling clays appear to be the most prevalent in the Tasmanian context.

The dominant agents of stone decay are water and salts (Spry 1981,p.55, & Spry 1988,p.37), and the importance of these agents can be seen in most of the decay modes described below.

5.3.1 Mechanical abrasion, impact, vibration, structural failure

These are universal problems affecting sandstone durability. The degree to which a building will be affected by such problems depends partly on the stone strength, and partly on the "mechanical environment" and design of the building. These causes of decay can be minimised by careful construction of a building to minimise abrasion, impact, vibration and structural failure, and by use of the strongest stone in parts of the building most vulnerable to these problems.

Thus, for instance, stone paving is particularly vulnerable to abrasion (feet) and impact (heavy dropped items), and should be of high abrasion resistance and high flexural strength in order to resist such stresses. Both abrasion resistance and flexural strength are essentially functions of the type and strength of intergranular bonds.

5.3.2 Thermal stress failure

Caused by repeated expansion and contraction of stone due to repeated hot-cold cycles. The most important hot-cold cycle is the diurnal (day/night) cycle. The parts of a building most at risk from thermal stress failure are those parts experiencing the widest variations in temperature; these are generally the parts exposed longest to sunlight during the day. In Tasmania, these are the northern parts of buildings; south-facing parts which are in shadow

all or most of the day will experience a narrower diurnal temperature range.

Thermal stress causes sandstone failure by cyclic stressing of the bonds between sand grains. Since these bonds largely determine the strength of sandstone, those stone most resistant to thermal stress will be the mechanically strongest stones.

Differences in the co-efficient of thermal expansion between different minerals in a sandstone may accelerate thermal stress failure. This is particularly important if salts such as halite are present in pore spaces. Halite has a higher co-efficient of thermal expansion than does quartz, and may thus place a high differential thermal stress on grain bonds during thermal stress cycles (*see* Winkler 1973,p.125).

Similarly, water trapped in pore spaces will expand and contract with temperature changes to a greater extent than will quartz (Winkler 1973,p.110-111), resulting in disruption of stone bonds due to differential stressing under a combination of wet/dry and hot/cold cycling.

Thus, susceptibility to thermal stress failure appears to be governed by the strength of intergranular bonds, the porosity (allowing entry of salts and moisture), and by the types of mineral present.

5.3.3 Alteration and solution of unstable minerals

The dissolution of soluble compounds in sandstone may lead to decay either by weakening intergranular cements, or by migration and re-precipitation of mineral matter in surface layers, causing case-hardening and ultimately exfoliation.

Dissolution of calcareous cements is unimportant in Tasmanian building sandstones, which rarely if at all have any significant calcareous content. However, halite and gypsum may occur in *in situ* sandstone deposits (Sharples 1984), and migration of these salts in building blocks may result in both case-hardening and salt attack (*see* Section 5.3.8).

Minerals such as feldspar and mica may react through leaching and hydrolysis to form clays (Winkler 1973, p.146), resulting in weakening of stone through an increase in clay content.

Minimal content of unstable minerals is required for durable building sandstone.

5.3.4 Acid attack

Acid attack may cause accelerated solution of acid-soluble minerals in sandstone. Acid attack can occur in sandstones when pyrite in the sandstone reacts with water to form sulphuric acid. Small quantities of pyrite may occur in some Tasmanian sandstones, but the acid attack process does not appear to have been important in the Tasmanian environment.

More commonly overseas, acid attack results from interactions with atmospheric pollutants (*see* Amoroso & Fassina 1983 for a detailed treatment). This has become a major problem with historic buildings in Europe, but is not a serious problem in Tasmania partly because atmospheric pollution has not reached significant levels, and partly because Tasmanian sandstones have few mineral components (eg, calcareous cements) which are readily attacked by acids.

5.3.5 Organic processes

Stone decay can be caused by the chemical action of bacteria, algae, fungi, lichens, mosses and the presence of phosphoric and nitric acids in bird droppings, or by the physical action of plant roots or boring animals.

In general, physical organic decay processes are minor in the Tasmanian building environment, and can be kept to a negligible level by periodic gentle cleaning of buildings. In Tasmania, some cleaning is provided by regular rainfall.

However, micro-organisms living within damp stone pores are considered (Spry 1981) to possibly be significant agents of stone decay, in that they produce acids and salts which may contribute to the weathering of stone.

5.3.6 Gypsum growth

Gypsum growth in sandstones is essentially a form of salt attack. Gypsum can occur naturally in Tasmanian sandstones (Sharples 1984), or may form in the stone around mortar joints, by the reaction of trace atmospheric sulphur (eg, from car exhausts and industry) with calcium derived from the mortar.

Some cases have been noted in Tasmanian buildings (eg, St. Johns Anglican Church, Launceston) where gypsum growth in pore spaces has caused crumbling of sandstone around mortar joints (see Plate 5.1). Cracking of stone parallel to mortar joints may also result from gypsum formation in the stone causing case-hardening adjacent to the joints.

5.3.7 Wet/dry cycling

Even in the absence of hot/cold cycling or of salts, sandstone decay can result from simple wet/dry cycling, resulting in expansion/contraction cycles, caused by atmospheric humidity changes or rainfall periods. Winkler (1973,p.111) records quartz sandstone expansions of 0.01 - 0.044% through simple wetting.

The expansion of sandstone through simple wetting is thought to be caused by the expansion of clays of any sort (Dunn & Hudec 1965,*in* Sengupta 1975). Although the greatest expansion with wetting is achieved by "expanding lattice" clays (eg, smectite) which take up water between unit layers within clay crystals ("intra-crystalline swelling", *see* Section 5.3.9), all clays will take up water in external clay crystal surfaces, causing a degree of expansion of clay aggregates by "inter-crystalline swelling" (Gillot 1987).

Since clay masses within sandstone not only expand but also weaken with wetting, repeated wet/dry cycling can lead to failure of intergranular bonds through repeated strain fatigue.

Certain other minerals, including hydrated salts, may expand or contract with moisture content variations, causing decay for similar reasons to clay expansion/contraction cycles.

The above decay modes, taken separately, are minor in Tasmanian conditions. The two decay modes which are responsible for most observed decay in Tasmanian sandstone buildings are salt attack ("salt damp") and expansion/contraction of swelling clays. Aspects of other decay modes may, however, be important contributing factors in these latter two.

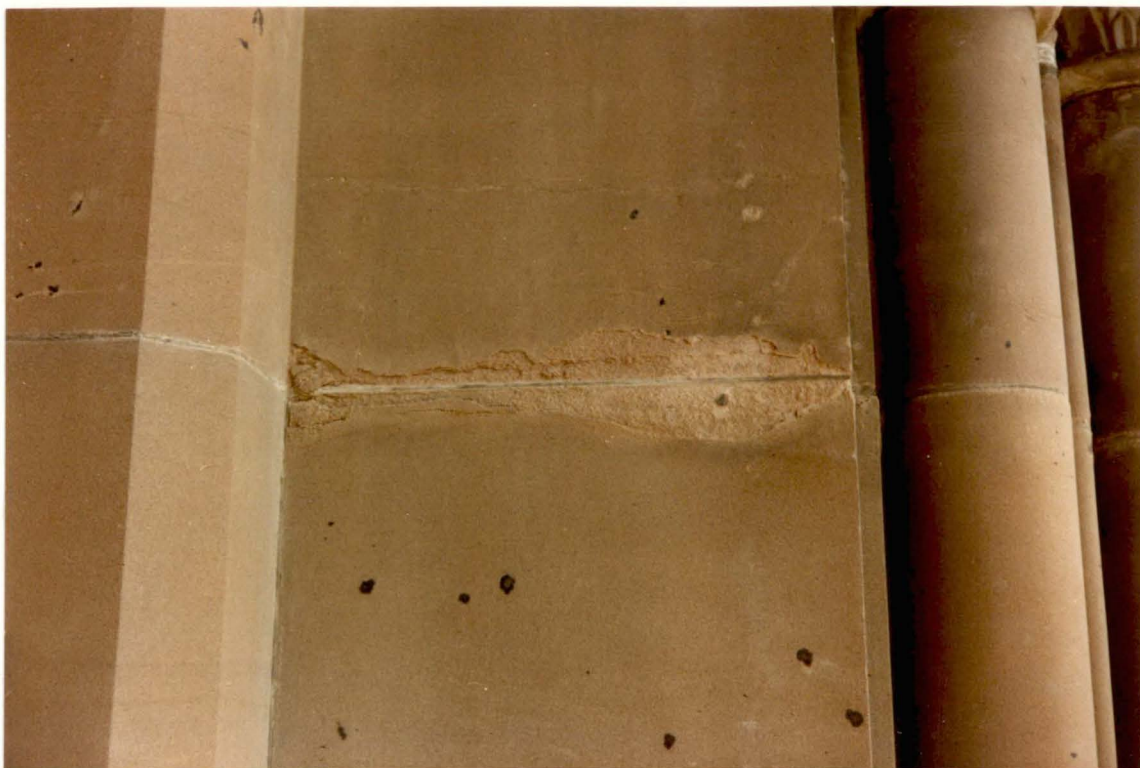


Plate 5.1 Decay resulting from gypsum growth around a mortar joint. "Patersonia" (Nunamara, Source 25) sandstone in St. Johns Anglican Church, Launceston (1825).



Plate 5.2 Severe decay and discolouration of Early Triassic sandstone due to rising damp and salt attack. Corner of Harrington and Warwick Streets, Hobart.

5.3.8 Salt attack

Salt attack is a significant sandstone decay mode in many parts of the world, including Tasmania. Salt attack occurs when water containing dissolved salts enters the pore spaces of sandstone, and precipitates salt crystals there. The salt crystals may then begin to exert pressure on pore walls, and thus upon intergranular bonds, leading eventually to failure of bonds and so to gradual crumbling or other types of stone decay.

The exertion of pressure on pore walls by salt crystals is caused by four mechanisms (Spry 1981):

- (1) Crystallisation - stress due to growth of crystals.
- (2) Changes in degree of hydration - hydrated salts change their crystal size as their degree of hydration changes, placing varying levels of pressure on pore walls with wet/dry cycles.
- (3) Action of deliquescent salts - an extremely aggressive mechanism occurring in certain (uncommon) "deliquescent" salts: the absorption of moisture produces a solution which can change hydration of salt and/or cause crystal growth on drying, both leading to stressing of grain bonds.
- (4) Thermal expansion - as mentioned above, differential thermal expansion/contraction of salt crystals can exert significant pressure on pore walls and intergranular bonds.

A large literature exists on the effects of salts on sandstone masonry. Useful references include Winkler (1973), Amoroso & Fassina (1983), and Spry (1978, 1981). Salt attack in the Tasmanian Port Arthur ruins was discussed by Cripps & Spratt (1979).

Salts in sandstone masonry can be derived from the stone itself (Sharples 1984), groundwater, airborne salt-sea aerosols, or from other sources.

Spry (1981) lists four classes of salts having varying degrees of aggressiveness:

- (1) Low aggressiveness: eg, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (gypsum)
- (2) Anhydrous stable salts, moderately aggressive: eg, NaCl (halite), KCl.
- (3) Efflorescent hydrous salts, very aggressive: eg, $\text{Na}_2\text{SO}_4 \cdot \text{H}_2\text{O}$, $\text{Na}_2\text{SO}_4 \cdot 7\text{H}_2\text{O}$, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$
- (4) Deliquescent hydrous salts, extremely aggressive: eg, $\text{CaCl}_2 \cdot \text{H}_2\text{O}$, etc (*see* Spry 1981, p.58 for a more complete list of salts involved in sandstone decay).

Of these salts, common salt (NaCl - halite) is the dominant salt involved in salt attack in Tasmanian sandstone buildings (and indeed in masonry in general, Spry 1988, p.39). Work at Port Arthur (Cripps & Spratt 1979) has shown that the salts involved there were mainly chlorides and sulphates of sodium, calcium, potassium and magnesium (in descending order of concentration).

Spratt (1982) noted that the effect of climatic conditions, alternations in temperature and humidity, and the action of sun and wind result in the alternate wetting and drying of exposed surfaces. The net effect of the periodic evaporation of absorbed moisture is a crystallisation of salts. During evaporation the salt solution may become super-saturated and the contained

salts crystallise out of solution either on or below the evaporating surface.

The crystallisation of the salts, their partial redissolving by extra water followed by more evaporation and crystallisation will cause disruption of weak materials or surfaces. The salt corrosion process can be described by the equation (*from* Cripps & Spratt 1979):

SUSCEPTIBLE MATERIAL + SOLUBLE SALT + WATER + EVAPORATION = MATERIAL DISINTEGRATION

Disintegration always involves all of these parameters, and will not occur in the absence of any one of them.

The formation of salt crystals from a liquid solution in masonry pores puts pressure on pore walls, causing internal stress as the crystals grow. Changes in degree of hydration cause changes in crystal volume, resulting in increased pressures. In general, low temperatures and high humidities produce the highest pressures; high temperatures and low humidities the lowest pressures.

The Tasmanian climate, particularly in winter, tends to low temperatures and high humidities, thus increasing the effectiveness of the salt attack process.

The most common pattern in Tasmanian buildings is that salt attack results from rising (groundwater) salt damp, so that damage generally occurs within one metre above ground level, at which point evaporation balances capillary rise of the salt waters. In such cases we usually find that the one metre zone of decay displays discolouration, salt efflorescences, and the presence of undercutting crumbling cavities (see Plate 5.2).

Other patterns of salt attack may occur when sea-spray, falling damp, or other situations are involved. Stone buildings close to salt seawater, and particularly in Hobart those buildings with parapet walls, are subject to severe salt attack at roof level from salty aerosols. The Port Arthur buildings are notable for salt attack at both top and bottom of walls.

A great deal of work has been undertaken to develop methods of protecting buildings from salt attack by methods such as damp-coursing to thwart the rise of the damp, and so forth. However, the present project is not directed towards this aspect, but rather towards determining which sandstones will have the greatest natural resistance to salt attack.

It would seem on conceptual grounds that the two most important factors in resistance to salt attack are the porosity of the stone (which governs the quantity of salt solution which can enter and precipitate in the stone), and the stone strength (which is to say, the strength of the intergranular bonds, which determine the degree to which the stone can resist the forces applied by the growth and expansion of salt crystals). It can be expected that the stones most resistant to salt attack would be those with the best combinations of low porosity and high strength. As discussed in Chapter Six, this prediction broadly is supported by the results of cyclic salt crystallisation tests.

However, simple effective porosity and simple strength do not alone fully determine sandstone resistance to salt attack. It is generally considered that pore size distribution is an important consideration (J. Heiman, *pers. comm.* to P. Spratt 1985), with high proportions of finer pores causing a significant lowering of durability.

In regard to strength, cyclic stresses such as are imposed by repeated wetting and drying during salt attack cause a lowering of stone strength as a result of rock fatigue. It is this

fatigue which ultimately leads to failure of intergranular bonds. However, Singh (1988) showed that the fatigue strength of sandstones was proportional to their uniaxial compressive strength (although Singh specifically studied greywacke sandstones, similar conclusions probably apply to quartz arenites).

Since sandstone strength is lowered during wetting (see Sections 2.5.3, 2.5.5), the degree of strength loss during the wetting cycles of the salt attack process is particularly important; the more resistant sandstones will be those having the least strength loss upon wetting.

Decay due to salt damp does not occur throughout entire buildings, but is concentrated in certain vulnerable parts. This results from the fact that the salt attack process depends on the interaction between its various components (salts, water and evaporation).

Salt attack decay occurs at or just below the surfaces of sandstone blocks, since the salts precipitate when water evaporates from the surface. Often the precipitated salt will be visible as "whiskers" growing outwards from the surface of the stone - these are known as "efflorescences". More commonly, the salt crystallises at or just below the stone surface. This can cause the stone to decay by individual grains crumbling away from the surface, giving rise to characteristic concave crumbling, powdering or honey-comb surfaces.

Another type of decay occurs when the concentration of crystallised salt just below block surfaces produces a "case-hardened" surface layer. Since this layer may be stronger than the interior of the stone block (due to the salt "cementing"), it expands and contracts differentially in response to hot/cold and wet/dry cycles, eventually exfoliating due to failure along the inner boundary of the case-hardened layer.

It is probably not possible to find a Tasmanian sandstone which is not in some degree susceptible to salt attack, since the highest strengths and lowest porosities generally found in Tasmanian building sandstones are not sufficient to guarantee indefinite resistance to salt attack stresses. Therefore, it is essential when using Tasmanian building sandstones to not only use the most resistant sandstones, but also to design buildings in such a way as to protect the stone from salt and water insofar as possible, and to reduce the potential for temperature and moisture variations in the stonework.

5.3.9 Swelling clays

In contrast to the problem of salt attack, sandstone decay resulting from swelling clays has received relatively little detailed study.

Although all clays may swell to some extent with the addition of water (see Section 2.2.4), the most pronounced swelling occurs in those clays which experience "intra-crystalline" swelling (Gillot 1987) as a result of uptake of water between unit layers within clay crystals. Such intra-crystalline swelling is the subject of this section.

Clay minerals subject to intra-crystalline swelling include smectite (especially the variety montmorillonite), mixed layer illite/smectite, vermiculite, halloysite and swelling chlorite.

Vermiculite is in its fully hydrated state under normal environmental conditions, and only loses water and contracts upon being strongly heated. For this reason it does not display expansion/contraction cycles under normal conditions, and so is not considered a

particularly detrimental swelling clay. See also Section 2.2.4 (D).

Halloysite and swelling chlorites are rare in Tasmanian building sandstones (halloysite was only found in the Cobbs Hill sandstone - Source 23 - in the course of this study).

Smectite and mixed layer illite/smectite are very commonly found in Tasmanian Triassic sandstones, and are considered to be the most important clays displaying intra-crystalline swelling and resulting in significant sandstone decay under normal environmental conditions (see description in Section 2.2.4 (C)). The following discussion relates specifically to smectite and mixed layer illite/smectite clays.

The role of smectite (montmorillonite) swelling clays in the decay of building sandstones in Tasmania was first noted in the Port Arthur ruins. At the request of Mr P. Spratt, samples of sandstone used in the severely decayed Port Arthur convict buildings were analysed by the Tasmanian Department of Mines (Green & Woolley 1981), and were found to contain large quantities of mixed layer illite/smectite (up to 21% of total rock mineral matter, by volume, on the basis of the present work - see Appendix One). It was realised that this large swelling clay content, acting in combination with salt attack, could account for the severe decay of the Port Arthur stonework (Spratt 1982).

Subsequently it has been noted in other buildings throughout Tasmania that there is a strong correlation between the presence of significant quantities of smectite and poor stone durability. The highest smectite content measured in any Tasmanian building sandstone in the present work is 25% by volume (of total stone mineral content) for Kangaroo Point Green sandstone (Source 4). Buildings constructed of this stone show very bad decay (see Plates 5.4 & 5.5). In addition, lesser quantities of smectite in Tea-Tree and Linden sandstone have been related to decay observed in buildings constructed of those stones (Plate 5.6).

Under normal conditions the basal spacing of the smectite unit crystal lattice is between 12Å and 15Å. Wetting with resultant absorption of water can cause expansion up to a maximum of 21Å, while complete dehydration results in contraction to 9Å. Although normal environmental cycles are not sufficiently extreme to cause expansion and contraction over this full range, climatic cycling from wet to dry conditions will cause a degree of expansion and contraction of smectite crystals, and thus of smectite aggregates.

Expansion of smectite aggregates exerts pressure on intergranular bonds in a fashion similar to the action of salts in pore spaces. According to Winkler (1973, p.197), smectite can exert a swelling pressure of up to 9000 psi (62 MPa). With frequent wet/dry cycles (as occurs in the Tasmanian building environment), the repeated expansion and contraction of the smectite aggregates causes repeated straining of intergranular bonds, ultimately leading to brittle fatigue failure of the bonds (P.Spratt, *pers. comm.*). Singh (1988) has shown that the fatigue strength (the reduction from initial strengths caused by cyclic stresses) of greywacke sandstones is proportional to their (initial) compressive strength.

On the macroscopic scale, smectite swelling clay can cause sandstone blocks to fail in a number of ways, including:

Deep cracking - Bulk expansion and shrinkage of stone blocks may cause the opening of deep cracks. This is probably the cause of the failure of blocks of lithic sandstone in the Ouse Anglican Church (Source 19, see Plate 5.3).



Plate 5.3 Deep cracking in Upper Triassic lithic sandstone (Source 19), probably due to excessive smectite content. St. John the Baptist Anglican Church, Ouse (1843).



Plate 5.4 Severe exfoliation and rounding in smectite-rich Kangaroo Point Green Sandstone (Source 4). St. Marks Chapel of Ease, Bellerive (1852).

Surface cracking - Often as superficial polygonal fretting or "crazing" patterns on old worked stone blocks, and not to be confused with the "elephant skin" (pachydermal) cracking which may occur on the surface of some natural outcrops regardless of smectite content.

Edge cracking - Horizontal and vertical cracks parallel to and 10 - 20mm in from (mortar) joints between blocks. Common in high-smectite sandstone blocks, although possibly related more to gypsum formation and case-hardening in the stone rather than simply to the smectite content (see Plate 5.5).

Exfoliation - Spectacular exfoliation of surface layers $\approx 10\text{mm}$ thick, while possibly also related to case-hardening, is characteristic of some high-smectite sandstones (eg, Kangaroo Point Green sandstone; see Plate 5.4).

Splitting - May occur horizontally and/or along bedding planes in situations such as ledges where water pools and soaks into the stone (see Plate 5.6).

Crumbling and rounding of corners and edges - Results from the progressive splitting away of individual surface grains (see Plate 5.4).

The degree to which smectite can lead to decay of sandstone is not merely a function of the total quantity of smectite present in the stone, but is more importantly a function of the morphology and distribution of the smectite (Spry 1983). The morphology of intergranular layers and films is such that clay swelling in such layers can exert a more direct stress on intergranular bonds than clay in pellets and interstitial masses can do. Thus, quite small quantities of smectite in intergranular layers and films can have an effect on stone durability equivalent to much larger smectite quantities in pellets and interstitial masses (see Sections 2.3.4 & A 3.2.3, "Intergranular Texture").

Since the intergranular texture of Tasmanian sandstones was not measured for most specimens during this project, it is not possible to give more than a general indication of the effect on durability of the varying total quantities of smectite measured in sandstones.

It is clear, however, that the amount of smectite which is tolerable in a building sandstone depends on the application for which the stone is used. The Hobart and Launceston General Post Offices contain, respectively, Linden sandstone with up to 2%, and Tea-Tree sandstone with up to 2.5% smectite by vol. % of total mineral matter. In these buildings, sandstone blocks used in smooth vertical ashlar wall sections, which shed rainwater easily rather than absorbing it, show little or no decay. However, decay in the form of splitting has taken place along the underside of horizontal ledges, especially those with flat tops. It is thought that this mode of decay results from rainwater pooling on and soaking through the ledges, allowing the smectite to swell.

On the other hand, the Port Arthur and Kangaroo Point Green sandstones, with smectite contents of up to 21 - 25% (by vol. of total mineral matter), show bad decay in all applications including the relatively "safe" vertical ashlar wall applications.

Spratt (1982b) suggested that smectite-bearing stone will have a life of about 80 years when used in a situation where wet/dry cycling is experienced. This figure must undoubtedly vary depending upon the quantity and intergranular texture of the smectite present. Ideally, smectite-free sandstone should be used in all applications.



Plate 5.5 Cracking parallel to joints in high-smectite Kangaroo Point Green sandstone (Source 4). St. Marks Chapel of Ease, Bellerive (1852).



Plate 5.6 Splitting beneath ledges due to water soaking into smectite-bearing sandstone. Linden sandstone (Source 27), Hobart G.P.O. (1901).

Although proper recommendations will require study of smectite intergranular morphologies and distributions, the discussion above suggests that sandstone with total volumetric smectite contents of up to 3 -75% can be used in low stress situations where water is not readily absorbed into stonework, and is likely to show little or no decay in such situations over periods of at least 100 years (based on the period such stone has survived intact in the Hobart and Launceston G.P.O.'s). However, any stonework in high stress situations (ie, where water may tend to be absorbed by the stone) must use stone completely free of smectite in order to avoid decay occurring over a similar period. Stone with smectite contents of over 20% by vol. (in fact, probably over 5%?) should not be used in any situation, as they will experience considerable decay.

In summary, the susceptibility of sandstone to smectite swelling clay - related decay depends on the following stone characteristics:

- (1) Total smectite content.
- (2) Morphology and distribution (intergranular texture) of the smectite present.
- (3) Stone strength (ability of intergranular bonds to resist swelling pressures).
- (4) Porosity and permeability (governs rate and quantity of water soaking into the stone to cause smectite to swell).

It should be noted that sandstones susceptible to both swelling clay decay and other forms of decay such as salt attack, will exhibit accelerated decay if used in situations where both modes of decay are occurring.

Indeed, it has been suggested that the presence of sodium may cause smectite to flocculate, weakening clay bonds and accelerating the rate of decay in situations where smectite-bearing stone suffers salt attack. This process has not been demonstrated in the present work, however, and cases exist of *in situ* Tasmanian Triassic sandstones which contain halite and yet have retained a significant smectite content (eg, see Appendix 11: several horizons in the Quartz Sandstone Sequence drilled in DDH "Thorpe" contain both halite and smectite; if the presence of halite salt caused the smectite to flocculate, it might be expected to have been removed by groundwater flow).

5.4 THE INFLUENCE OF STONE WORKING AND APPLICATION ON SUSCEPTIBILITY TO DECAY

The rate at which stone will decay depends not only upon the properties of the stone, but also on the nature of the building environment and the manner in which the stone is prepared and used. The nature of the building environment determines which agents and processes of decay will take effect; it is the interaction between the stone and its environment which ultimately determine its durability.

5.4.1 Quarrying methods

Amoroso & Fassina (1983,p.7) briefly discuss the effect of different quarrying methods on stone durability. Methods which produce intense shocks or vibration (eg, blasting and/or the use of pneumatic drills or hammers) will produce micro-cracks in the stone. Such micro-cracks increase the porosity of the stone, decrease its strength, and provide more flaws upon which chemical or salt attack can begin.

Blasting with gelignite should never be used in dimension stone quarrying, as it produces not only micro-cracks, but also large macro-cracks. Black powder and Cordex are less destructive, and are still commonly used, but may produce micro-cracking and are not acceptable for applications in which the highest stone durability is required.

Alessandrini *et al.* (1976, in Spry 1981,p.96) consider that sawing is the least harmful method of working stone. Available methods of extracting stone from the quarry by sawing include circular diamond saws mounted on rails on quarry benches, and similarly mounted large diamond-tipped chainsaws (eg, Kauffman saws), which can saw both vertically and horizontally to cut out large blocks.

Other relatively gentle methods of splitting out sandstone blocks in the quarry include the traditional "feather and wedge" method, and modern methods employing expanding "putties".

5.4.2 Curing and working of dimensionally unstable sandstone

Project specifications sometimes require that the large quarried blocks of stone to be used in a building should be allowed to stand untouched in the stone yard for a period of time after quarrying (typically three to four months) before being cut up and worked. In stone industry parlance, the purpose of this is to allow the stone to "cure" by drying out the "quarry sap".

In geological terms, the significance of "curing" is this: most sandstones contain a greater or lesser degree of clay bonds, which (whether smectite swelling clay or otherwise) all tend to soften and swell at least a little when saturated with water. Sandstone *in situ* in the quarry generally is at least partly saturated with groundwater ("quarry sap"). The stone will thus be slightly softer immediately upon quarrying than it will be after some months of drying in the stone yard has allowed the stone's moisture content to reach equilibrium with the atmosphere. It is unlikely that stone in the building environment will ever again reach the same degree of saturation, for such long periods, as occurs in the ground.

By allowing stone blocks to cure, the result is that by the time the stone comes to be worked, it will have hardened slightly, and may have shrunk fractionally, so having reached a state which is in equilibrium with the building environment where it will henceforth reside. It can therefore be confidently worked in the knowledge that the strength and dimensions of the worked blocks will remain more or less constant from that time on.

To work an uncured block and place it in a building while still "green" with "quarry sap",



Plate 5.7 Crack which formed in freshly quarried dimensionally unstable sandstone within days of being cut, worked and dried in the workshop. Elderslie Quarry "massive" sandstone (Source 26).

could potentially result in cracking of blocks or mortar joints if the block shrinks significantly when it is finally allowed to cure in the building.

Ideally, a good building sandstone should have a high proportion of quartz-quartz grain bonds, and a low proportion of quartz-clay bonds (see Section 2.3.4), so that it exhibits high strength with only a small wet/dry strength variation (see Sections 2.5.3 & 2.5.5). Such stone would experience negligible shrinkage with drying (ie, have low dimensional instability - see Section 2.5.9). With such a good quality stone, curing may be less critical, although it is always a desirable procedure.

However, in stone with a high degree of dimensional instability, curing is critical. Massively bedded sandstone from the Elderslie Quarry (Source 26) shows some of the problems associated with dimensional instability:

The massive Elderslie stone has a high degree of dimensional instability; tests conducted at the AMDEL laboratory (S.A.) indicated a shrinkage on drying of approximately 0.20% (A.Spry, *pers. comm.*, 1989, Sharples 1989b). This is attributed to a high proportion of intergranular clay films between quartz grains. Although only trace amounts of smectite swelling clay occur in the stone, the high proportion of other clay minerals bonding the grains still allows this significant drying shrinkage to occur.

When some blocks of the stone, fresh from the quarry, were cut up in 1989/90, it was found that a small proportion of the worked blocks were developing significant cracks (up to 1mm wide), which began to form within days or weeks of cutting the blocks, and could be observed to lengthen on a day-by-day basis (see Plate 5.7). These cracks commonly formed parallel to the bedding direction, although in some cases they formed at other angles, and in

locations which seemed to be related more to the shape of the cut block than to any natural structures in the stone (eg, cracks parallel to block ends, or radially about holes drilled through the blocks).

It appears that the effect of cutting the large quarry blocks into smaller blocks before they had cured was to accelerate the drying of the small blocks, since the water ("quarry sap") in them could evaporate out faster due to the smaller volume to surface area ratio. This caused the blocks to shrink at a rate which was too fast for the elastic properties of the stone to accommodate, and for the lesser overall strength of the smaller blocks to resist, so that in consequence the stone cracked.

Two methods of successfully handling a dimensionally unstable stone such as this can be proposed:

(1)

The preferable method is to properly cure the large quarry blocks before cutting them up to be worked. Curing may take from three to six months, or more. In a large block, the high volume to surface area ratio will result in evaporation, and thus shrinkage, occurring at a slower rate throughout the block as a whole. Not only will the slower, gentler shrinkage rate place less strain on the elastic response of the stone, but the greater overall strength of the larger blocks will allow the stone to better resist cracking in response to that strain.

Once the large blocks have fully cured and reached equilibrium with the atmosphere, and the elastic properties of the stone have fully adjusted to the shrinkage so that all strain within the blocks has been released, there should be no further shrinkage and cracking upon cutting into smaller blocks.

(2)

In cases where the stone is to be used as ashlar blocks in a wall where the blocks will be under a permanent load, it is possible to work the uncured stone provided it is kept in a saturated condition (eg, by regular spraying) from the time of quarrying through until the time the finished blocks are placed in the wall.

Once in the wall, the loading on the blocks should keep cracks from developing as the stone shrinks. This method cannot be guaranteed, however, and is far less desirable than using a properly cured or dimensionally stable stone!

5.4.3 Stone finishing and laying methods

As with quarrying, working and finishing methods should be chosen to produce the smallest possible amount of vibration and shocking of the stone. Amoroso & Fassina (1983) point out that working of stone surfaces with a mechanical bush-hammer produces much more detrimental surface micro-cracking than do gentler manual methods of finishing stone surfaces with hammer and chisel. If mechanical finishing methods are used, they need to be designed to produce as little intense vibration as possible.

The type of surface finish, or "dressing", of sandstone blocks commonly appears to exert a control on rates of stone decay. In Tasmanian sandstone buildings, the most common forms of dressing are irregular convex "rock-faced" finishing, chisel-picked finishing, and flat, smooth finishing. In some cases the stone is carved into complex shapes, or flat-surfaced with shallow parallel grooves (Spry 1981,p.25-26 gives a more detailed listing of the terminology for styles of sandstone dressing).

Observations during the present work seem to indicate that, as a general rule, rougher or more complicated surfaces are less susceptible to decay than flat smooth surfaces. For instance, the old Mines Department building in Davey St., Hobart, has (prior to restoration with better stone) been subject to severe decay due to its construction with high-smectite Kangaroo Point Green stone. It is noteworthy that the worst decay on vertical block surfaces occurred on smooth flat-faced blocks, whilst many of the pick-finished blocks remained in relatively good condition.

The reasons for these effects of surface finish on durability are not clear. In any case, surface finish is probably a much less significant durability factor in a stone which is good in terms of most other technical properties.

Most sandstones have a distinct strength and Ultrasonic Pulse Velocity anisotropy relative to the bedding direction, even in the (desirable) case of massively bedded sandstone which has no visible bedding planes. For this reason it is important that sandstone blocks (whether massive or distinctly laminated) should be laid in the correct orientation with respect to their bedding direction.

The correct orientation in which to lay sandstone blocks is with bedding planes (or bedding direction in massive stone) lying horizontal ("natural-bedded"). This ensures both the best mechanical load-bearing capacity, and also decreases the tendency for weaker laminae and stone portions to be attacked and split away from the main stone mass. Bedding direction should be marked on massive and indistinctly-bedded sandstone blocks prior to their removal from the quarry, in order to ensure that blocks can later be laid correctly oriented.

An inferior orientation is "edge-bedding", in which bedding planes are vertical and perpendicular to the face of the wall. Worst of all is "face-bedding", in which bedding planes are vertical and parallel to the face of the wall. In a face-bedded orientation individual laminae in distinctly laminated stone may exfoliate very easily.

Some strongly colour-patterned ornamental flagging slabs are commonly laid face-bedded in feature walls, in order to display their patterning to the best advantage. This can work if the individual slabs have no distinct internal laminations and have excellent technical properties in all respects (as is the case with the Molesworth stone, Source 29).

However, Cripps & Spratt (1979) have noted examples of edge and face-bedded blocks at Port Arthur, and distinctly laminated blocks have also been laid in these ways in some historic Hobart buildings. This was probably done because it is easier to dress laminated stone blocks by splitting them along bedding planes and using the bedding surfaces as vertical block faces. Many of these blocks can today be observed to be splitting and exfoliating badly.

5.4.4 Building "micro-environments"

As used here, the term "micro-environment" refers to both "micro-climate" (the variable exposure to water, temperature variations, wind, and so forth, which may occur in different parts of the same building) and to "detailing" (the shapes of individual blocks, which can affect their susceptibility to decay processes).

Spry (1981,p.56) has listed some of the most common micro-climatic factors which affect stone buildings in Australia, and in general his list is applicable to Tasmania.

The "aspect" of various parts of a building refers to the direction in which they face. In Australia, the following micro-climatic effects occur in walls depending upon their aspect:

South-facing walls	-Cool and damp most of the time; moisture and temperature fluctuations minimal.
West walls	-Often wetted by rain, exposed to wind; significant moisture fluctuations.
North walls	-Most extreme variations in wetting/drying and heating/cooling cycles, due to longest exposure to sunlight (heating and drying effect) during the day, and absence thereof during night.
Sheltered walls	-Walls sheltered by verandahs, vegetation or adjacent buildings are not de-salted by rain, but are not dried by the sun, therefore wet/dry cycles are less pronounced.

Since the effectiveness of decay processes such as thermal stress, salt attack and clay swelling depends more on the degree to which temperature and moisture fluctuate in walls, rather than on actual temperatures or moisture contents, the walls most susceptible to decay will be north and west facing walls. Sheltered and south facing walls may be quite wet and even salty, but will experience less decay because their temperature and moisture contents fluctuate to a much smaller degree than do north and west walls.

Significant decay commonly occurs in the parts of a building where wind most frequently impinges. Not only sunlight, but also wind increases evaporation of water from stone surfaces, causing drying and salt crystallisation cycles. Poorly planned heating or air-conditioning of buildings can have similar effects, particularly in basement areas.

In walls of all aspects, the base course and basement portions of a building are particularly susceptible to rising (commonly salty) damp from groundwater. The effects (discolouration, salt efflorescences, cavity formation) are generally apparent in a wall for approximately one metre above ground level. In order to protect against the effects of rising damp, base-courses should ideally be constructed of a very high quality durable stone (resistant to salt attack), and in any case should be properly damp-coursed to halt the rise of groundwater.

"Detailing" is an important control on stone decay (P. Spratt, *pers. comm.*). The example of splitting occurring beneath horizontally-topped ledges (due to pooling and soaking in of rainwater, allowing clays to swell) has already been mentioned (Section 5.3.9).

In general, the effect of detailing on stone decay appears to be related to the degree to which stone shape either allows water to soak in or to quickly run off the surface of stone blocks.

Plain vertical ashlar walls with no detailing are the most resistant to decay, since they experience only superficial wetting with rapid run-off, so that moisture fluctuations in the body of the stone are minimal.

Window ledges, string-course ledges, cornices and parapets are particularly susceptible to decay, as they allow water to soak right through the stone, causing major wet/dry cycles within the stone in response to wet/dry cycles in the surrounding environment. This facilitates the processes of decay through clay swelling and salt crystallisation cycles. Decay in such ledges may take the form of splitting along the top of the ledge, or can occur as crumbling of the underside of the ledge due to water falling onto the ledge, soaking through

and picking up salt within the stone, and then evaporating from the bottom of the ledge, leaving a high concentration of salt behind.

The design of ledges with sloping upper surfaces to shed water may improve water run-off, and decrease these forms of decay. In any kind of detailing or carving of sandstone, it is necessary to keep run-off in mind, and to design all detailing to shed water rather than allow it to pool or be retained.

In summary, very durable stone is required for base-courses and detailing such as ledges, parapets and cornices, especially on the northern and western sides of Tasmanian buildings. Less durable stone can be acceptable for plain vertical ashlar walls. Attention must be paid to protecting stone from decay by means of proper damp-coursing and appropriate detailing of stone-work.

5.4.5 Building "macro-environments"

The environment in which a building as a whole exists largely determines the nature of the micro-environments within the building. Important "macro-environmental" factors include the local climate and the presence of decay agents such as salt sources, pollution and vibration.

According to Spratt (1982), the climatic factors of greatest importance to stone decay are rainfall, temperature, wind and humidity. Spratt notes that decay is facilitated by "a large number of wet/dry cycles, a consistent rainfall of showers without heavy flushing rains and which occur regularly throughout the year so that crystallisation, partial dissolving, recrystallisation or hydration changes can occur; evaporation from wind or sun interspersed with frequent light rain; simultaneous high humidity and low temperature".

These factors are typical of the climate in parts of Tasmania including Hobart. When added to a coastal location providing sea-salt aerosols, such conditions constitute a very aggressive environment. The absence of heavy driving rains is important, since it is only such heavy rains which can flush salt out of stone.

On the other hand, although the Tasmanian climate is aggressive in the sense of having wide variations in its wet/dry cycles, it does not normally show enough temperature variation for thermal stress or frost action to become major decay processes.

A minimally aggressive climate would be one having very small temperature and moisture variations. Such a climate is not found in Tasmania.

The proximity to other agents of decay is important. Such agents include salt (eg, areas with salty groundwater or close to salt sea), pollutants (polluted city environments) or vibration (areas close to busy traffic, heavy machinery, etc).

CHAPTER SIX

DURABILITY ASSESSMENT OF BUILDING SANDSTONES

6.1 INTRODUCTION

There are three approaches to assessing and predicting the durability of sandstone in the building environment (Spry 1983,p.54):

- 1) Inferring predicted stone behaviour from measurement of sandstone properties.
- 2) Simulation of decay processes by subjecting stone samples to accelerated decay tests.
- 3) Observing actual behaviour of stone in existing buildings.

This chapter discusses the merits and drawbacks of each approach.

6.2 MEASUREMENT OF STONE PROPERTIES

The susceptibility of sandstone to fail in response to a given decay process is determined by the properties of the stone. In principle, therefore, the ideal method of determining sandstone durability is to infer it from measurements of those properties which determine to stone's response to stresses in the building environment.

At present, knowledge of the ways in which stone interacts with environmental conditions to yield particular types and rates of decay is essentially qualitative. It is possible to say, with reasonable confidence, that certain properties of a stone will make it susceptible to certain types of decay under certain conditions. However, it is difficult use quantitative measurements of stone properties to quantify the rate and degree of decay which can be expected in a stone.

Complications in prediction of durability also arise from the interaction between different stone properties, and from the differing stresses a stone may be subject to under differing environmental conditions:

1) Interaction between stone properties

There is no simple relationship between the suite of properties possessed by a particular stone, and the rate and type of decay to which that stone can be expected to be susceptible.

For instance, a stone with a high porosity would be expected to be particularly susceptible to salt attack, since the high porosity will allow entry and crystallisation of large quantities of salt within the stone. However if the same stone has a high strength (and a high wet/dry strength ratio) resulting from a high proportion of intergranular silica bonds, then it will not be as susceptible to salt attack as the porosity might indicate, as the strong intergranular bonds will be better able to resist the stresses imposed by salt crystallisation in the pore spaces.

Similarly, the presence of the swelling clay smectite is held to be deleterious to stone durability. However if the stone also has a low porosity and high strength, the deleterious effect of the smectite will be much less significant (this situation applies in the case of Cobbs Hill stone (Source 23), for instance).

Again, the presence of a relatively high proportion of clay matrix in a sandstone may or may not be deleterious, depending upon whether the clay is predominantly present in the form of interstitial clay masses, or as intergranular layers and films (see Section 2.3.4).

It is not possible to predict stone durability by a simple tallying up of measured stone properties; rather it is necessary to understand how the various properties of a stone will interact in response to a particular stress. Predicting stone durability in this fashion is an essentially qualitative process, requiring experience and an understanding of both the geological properties of stone and the processes of stone decay.

2) Response of stone to differing stresses

The susceptibility of a particular stone to decay depends not only upon the properties of the stone, but also upon the degree and type of decay processes which are prevalent in the particular situation in which it is used (see Sections 5.4.4 & 5.4.5).

A stone may have "high durability" in a situation in which it is subject to minimal stresses, or in which the prevalent stresses are ones to which the stones properties make it resistant. On the other hand, the same stone may have "low durability" in another situation in which it is subject to stresses of a type to which the stones properties make it susceptible.

Therefore it is not possible to make a blanket statement that a particular stones properties make it either a "high" or "low" durability stone. Rather, a stone may have either high or low durability in particular situations.

The durability of sandstone cannot be assessed in isolation from the purpose for which it is proposed to be used.

Comments are offered below on particular sandstone properties which may be measured to yield an indication of sandstone durability:

6.2.1 The significance of particular stone properties in assessment of durability

The significance of particular measured sandstone properties in determining sandstone durability have already been discussed in Chapters Two and Five. Techniques for measuring these properties are given in Appendix Three.

The following notes give a brief indication of the value and significance each important measured property is considered to have as a means of assessing sandstone durability. Macroscopic physical properties are not considered here (eg, jointing, bedding - see discussions in Chapter Two & Seven); this section concentrates on properties which can be measured as part of a laboratory assessment of durability.

Mineralogy

Mineralogy is fundamentally related to durability, since the proportions of chemically and physically stable and unstable minerals relate directly to the ability of the stone to withstand chemical and physical stresses.

Quartz is the most stable mineral commonly found in sandstone, so that greater quartz content should correlate with greater durability. Conversely, greater proportions of less

stable minerals (eg, feldspar, mica, clay, carbonate) will correlate with lowered durability. Quartz and clay minerals constitute by far the greater proportion of Tasmanian sandstones.

However, although the volumetric proportions of quartz and clay are important factors in durability, it is considered that their morphological and bonding relationships to one another are even more significant (intergranular texture, see below).

Ferruginous cements may play a small role in increasing stone strength, but this role is normally overshadowed by the dominating effects of quartz - clay intergranular textures.

Particular detrimental minerals may be of special significance in determining sandstone durability. The swelling clay smectite is the most important of such detrimental minerals in Tasmanian sandstones.

Texture and intergranular texture

Basic textural properties such as grainsize, sorting, and grainshape play a role in determining sandstone strength and porosity (and thus, durability). However these parameters show little significant variation amongst the sandstones most commonly used in Tasmania for building, and thus do not constitute a major variable. Grain orientation (fabric) is important, since a high degree of common orientation leads to a tendency to split.

Intergranular texture, which is in part a function of sorting, grainshape, packing, compaction, quartz cementation and other textural properties, is of very great significance as a determinant of sandstone durability. This is because intergranular texture is the basic determinant of a number of important derived properties related to durability, including stone strength, wet/dry strength ratios, porosity and dimensional instability. Although all these derived properties should be measured directly, it is of great value to also quantify the features of the basic intergranular texture, since this gives a clearer understanding of the causes of the derived properties.

However, although quantitative measurements of intergranular texture can be obtained (quartz/quartz contact %, etc), it is difficult to define precise cutoff values for these parameters which can be used to distinguish high and low durability sandstones. Intergranular texture is considered to be very important in a qualitative understanding of sandstone durability, but is presently more restricted in its ability to yield quantitative assessments of durability.

Strength (compressive, tensile, flexural)

Compressive and flexural strengths are most directly important in determining a stones response to loading and bending stresses, respectively.

Flexural strength is therefore an important determinant of sandstones mechanical durability when used in certain situations such as thin veneers or paving slabs, but is not greatly relevant to other aspects of durability.

Compressive strength is of little relevance to durability *per se* , since virtually all sandstones have sufficient strength to withstand normal loadings in a building. However, it is relevant in another sense (see below).

Tensile strength is of greatest direct relevance to determining sandstone durability in response to decay processes such as salt attack and clay swelling, since these processes place a tensile strain on intergranular bonds in the stone. There are practical difficulties in

measuring tensile strength directly (see Section 2.5.5), but it can be measured indirectly using the Point Load Strength Test (Appendix Three).

However the Point Load Strength test may produce a wide scatter of results since it tends to cause incipient fractures in the stone to fail easily, giving a distorted value for the strength of the material (Section 2.5.5). Compressive strength testing has the opposite effect of nullifying the effect of incipient fractures (by closing them up during the test), and so gives a more reliable scatter of results.

For this reason, and since compressive strength is proportionally related to tensile strength (Section 2.5.3), many workers prefer to use compressive strengths to give an indication of stone durability in response to salt attack, etc. Point Load Strength Index has been used during the present project due to the easier availability of the necessary equipment.

Strength anisotropy (variation with respect to bedding direction) and wet/dry strength ratios are important sandstone properties controlling sandstone durability, and the orientation in which stone blocks should be laid in a building.

Porosity (Effective porosity, water absorption, bulk density)

Water is one of the most important agents of decay (see Section 5.3), and it is porosity which determines the amount of water which can be taken up within sandstone. In general, lower porosity means less water can be taken up, resulting in lowered stresses being imposed on the stone by decay processes.

Absolute porosity is a measure of the total volume of porosity existing within a sandstone. However, since not all this porosity is accessible to water, it is of more relevance to measure effective porosity (volume %), which is a measure of the amount of water which can actually be taken up into sandstone under normal conditions. Water absorption (weight % of water uptake) and dry bulk density are related properties measured in the same test.

Pore size distribution is considered to be more important in durability than simple gross effective porosity (J. Heiman, *pers. comm.* to P. Spratt, 1985). Pore size distribution may be determined by mercury porosimetry or the suction plate technique (Anon. 1975). Neither technique was attempted in the present study.

Dimensional Instability

Dimensional instability is a measure of the expansion and contraction of stone with wet/dry and hot/cold cycles. It is a function of mineralogy (including clay content), intergranular texture and co-efficient of thermal expansion of stone, and provides a measure of the physical stability of stone.

Since greater physical stability is related to reduced susceptibility to decay processes, dimensional instability is an important parameter related to stone durability.

Ultrasonic Pulse Velocity

Ultrasonic Pulse Velocity (UPV) measures the rate at which sound propagates through a material, and is dependant upon the density and elastic properties of the material. In the case of sandstone, UPV is considered to be dependant upon the effects of mineralogy (related to density, and including quartz and clay %), intergranular texture (including percentages of Quartz/Quartz & Quartz/Clay bonds, which relate to both elasticity and strength), porosity (related to density), and discontinuities such as micro-fracturing (see Section 2.5.7).

During this project, a detailed study of UPV was made with the object of determining the degree to which it correlates with other durability-related sandstone properties, and to assess the usefulness of the technique as a means of rapid assessment of sandstone quality. The results of this study have been presented in a separate major report (Sharples 1985a), which is reproduced in this thesis as Appendix Six.

In brief, the UPV of 49 sawn specimens was determined (the final value used for analysis being an average of UPV measured parallel and perpendicular to bedding). The effective porosity, dry Point Load Strength Index, total clay content and smectite swelling clay content of each specimen was also measured.

The correlation between UPV and the other measured properties was determined by regression analysis. The correlations obtained were expressed in terms of the figure ($100r^2$), which is the degree to which variation in one of the parameters correlates with variation in the other parameter, where "r" is the correlation co-efficient determined by the regression analysis. In these terms, where $100r^2 = 100\%$, the correlation is a completely linear relationship, while a result of $100r^2 = 0\%$ would mean that no correlation whatsoever existed.

UPV was first compared to each of the other measured properties individually, and then in various combinations.

The statistical analysis showed that UPV has no significant correlation with either smectite content or total clay content, taken in isolation. However, correlating in a logarithmic fashion, UPV has a 47.99% correlation with Point Load Strength Index. Further, although porosity alone has only a 23% logarithmic correlation with UPV, the combination of strength (S) and porosity (P), in the form (S/P), has a 50.8% logarithmic correlation with UPV (see Fig. 6.1).

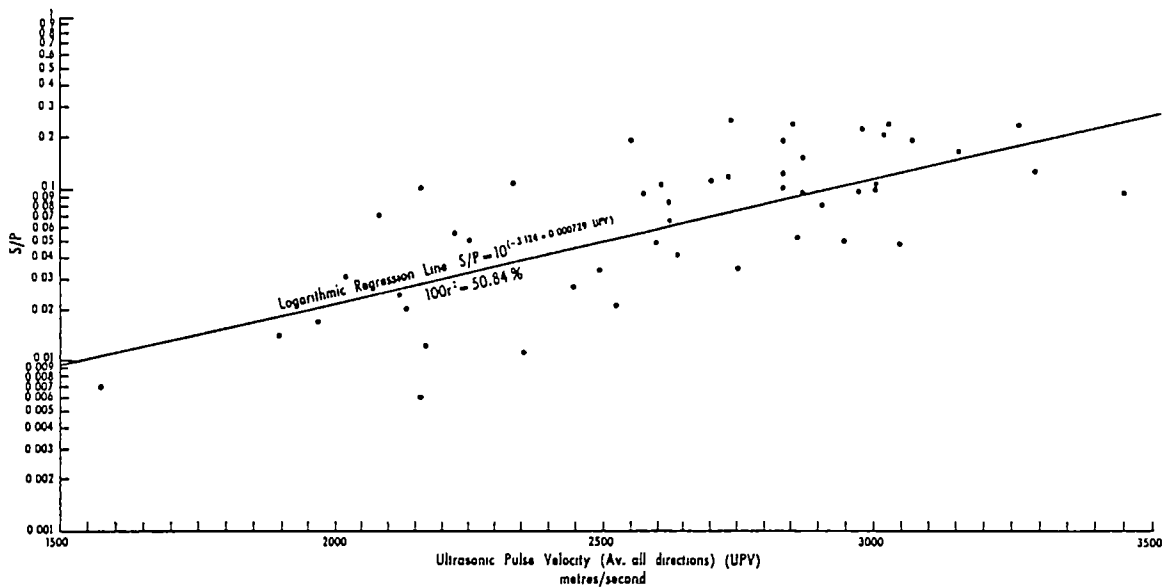


Figure 6.1 Relationship between Ultrasonic Pulse Velocity and Strength/Porosity (S/P) in Tasmanian building sandstones. (Copy of Fig. 4.6 of Sharples 1985a; see also Appendix Six)

The relationship (S/P) could be theoretically expected to correlate with UPV, since greater strength (= bonding between sand grains) should facilitate better transmission of sound waves, while greater porosity (= discontinuities caused by pore spaces) should inhibit transmission of sound.

However, the correlation obtained (50.8%) is still not an especially significant one, as it only accounts for half of the variation observed. It is probable that the correlation can only be enhanced to a significant level if a more complex multi-variate analysis is employed:

In the first place, to suggest that the relationship (S/P) should be directly correlated with UPV implies that each further MegaPascal of a stones Point Load Strength Index will increase the stones UPV to the same degree that each 1.0% of increasing effective porosity will decrease it. It is of course highly unlikely that such a simplistic relationship would hold true.

A more valid equation relating sandstones porosity and strength to its UPV would take the form:

$$UPV = a.S/b.P$$

Where:

UPV	=	Ultrasonic Pulse Velocity
S	=	Sandstone strength (eg, dry Point Load Strength Index)
P	=	Sandstone porosity (eg, effective porosity)
a, b	=	Constants of proportionality

It would be necessary to determine the constants of proportionality (a & b) through continued laboratory testing and statistical analysis to determine constants giving the best fit to the data.

Beyond this, it is possible that a better correlation would be obtained if, instead of trying to relate UPV to simple strength, it were instead related to those aspects of intergranular texture which are likely to have the dominant effect on controlling both strength and propagation of sound (ie, Quartz/Quartz contact %, Quartz/Clay contact %).

Furthermore, sound transmission is considered to be significantly slowed down by the presence in the stone of not only "large" pore spaces, but also very fine fractures. Instead of trying to compare UPV with simple effective porosity, which encompasses not only larger pores, but also fine fractures and water-absorbent clay masses, it could be more useful to compare the UPV with the stones content of pore spaces and fine fractures, determined separately.

Further, since quartz and clay have different sonic velocities, the total quartz and total clay content of the sandstone are both likely to play an important role.

In order to obtain a correlation of significantly better than 50% between UPV and other sandstone properties considered to influence stone durability, it will be necessary to conduct a complex multi-variate analysis which takes all of these variables into account, and which incorporates suitable proportionality constants.

Such a complex analysis may not be of great value, however. It is already apparent from the existing work (Sharples 1985a) that UPV does not have a linear correlation with any one other sandstone property. UPV is not a method for measuring other sandstone properties, but rather can best be regarded as a property in its own right, which is the resultant of a number of other sandstone properties which are relevant to stone durability.

UPV is best considered as a rapid, convenient and non-destructive means for distinguishing, in a fairly broad way, between better and worse stones in a related suite of samples. In using UPV in durability assessments, it will always be necessary to obtain additional data on other specific sandstone properties by other laboratory tests. This applies especially to information such as swelling clay content, of which UPV gives no specific indication.

Once the basic properties of a suite of samples have been determined, UPV then becomes a useful tool in distinguishing between higher and lower durability members of the suite. It can possibly find its best application as a quality control technique on related sandstone blocks whose properties and durabilities are in general already known, but which display a degree of variation between individual blocks. Sharples (1985a, Appendix Six) gives a discussion of the various methods and limitations in applying UPV to the comparison of the likely durabilities of related sandstone blocks in existing buildings, large cut blocks, drill core and in quarry faces.

6.3 ACCELERATED DECAY TESTING

The object of accelerated decay testing is to subject samples of differing sandstones to a carefully controlled process which is designed to simulate, in an accelerated form, stresses which may be imposed upon stone in the building environment. By quantitatively measuring and comparing the rates at which different sandstones decay in response to this artificial stress, it is possible to produce a quantified measure of the "durability" of various stones in response to the applied testing process. It is considered that there is likely to be a consistent relationship between the durability of stone in such an artificial test, and the durability of the stone in response to actual environmental stresses in the building environment.

The type of accelerated decay test most commonly employed is the Sodium Sulphate Soundness Test (Full Immersion Method), which is fully described in the Standards Association of Australia draft standard DR 87001 (Jan. 1987, see Appendix Three of this thesis). This test involves cyclic immersion of sandstone in a solution of sodium sulphate, with regular periods of drying. The aim of the test is to simulate, in an accelerated form, the process of salt attack. Salt crystals are allowed to grow in pore spaces within the sandstone, and the resulting decay of the stone is measured quantitatively.

Other tests may also be employed, including partial immersion methods. During the present project, an accelerated decay test involving sodium chloride salt, and applying a combination of soaking/drying and hot/cold cycles to enhance the stresses applied to the stone, was utilised (see Section 6.3.1 below).

Accelerated decay tests have the advantage that they give an easily quantified measure of the response of sandstone to an actual applied decay process, rather than merely attempting to predict decay from measurement of stone properties.

However, the disadvantage of accelerated decay testing is that it is somewhat simplistic (Spry 1983, p.54). The tests attack the stone by means of a single decay process, rather than the complex interaction of processes which are generally involved in actual building environments. Thus, the response of a stone to accelerated salt attack gives very little indication of whether it will be significantly affected by the process of swelling clay expansion and contraction over long periods, for instance (see Section 6.3.1 below).

Furthermore, even as a simple measure of a stone's susceptibility to salt attack alone, the

speed and intensity of the stresses created during a salt test creates are far more intense than the stresses of actual salt attack in a building, which occurs over periods of years rather than days. It is quite possible that the response of stone to salt attack which occurs slowly, over long periods, will be different to its response to a very rapid and intense bout of salt attack.

Accelerated decay tests are considered to be useful insofar as they yield a quantitative measure of sandstone response to a particular decay stress. The easily quantifiable and reproducible nature of the test allows the durability of different sandstones in response to this particular test to be compared directly. It is considered that this yields a useful comparison of the likely relative durabilities of various sandstone types in response to a range of decay processes encountered in the building environment.

However, because of the limitations of the accelerated decay test method, its results cannot be used in isolation to assess a stone's durability. It is essential to assess the likely significance of accelerated test results by also taking into consideration the measured properties of the stone in question and, preferably, by assessing the actual past performance of the stone in existing buildings.

6.3.1 Correlation of accelerated decay test results with sandstone properties and likely response to decay processes

During the early stages of this project, an accelerated decay testing program was conducted with the aim of attempting to determine the degree to which the results of accelerated decay tests could be shown to correlate with sandstone properties considered to control stone durability. The aim of this work was to attempt to assess the degree to which accelerated test results could give a useful prediction of the response of the stone to actual decay processes in the building environment.

The results of the testing program were initially presented in Sharples *et al.* (1984), and Appendix Seven of this thesis gives a complete copy of this original presentation. The accelerated decay test employed was a sodium chloride cyclic salt crystallisation test involving both soaking/drying and hot/cold cycles (see description of method in Appendix Three, A 3.5.2).

Since a number of deficiencies in the original test (and its interpretation) have subsequently become apparent, the following discussion only briefly summarises the important conclusions drawn from the test. However, the deficiencies of the test program are pointed out, and the proposed design of a better test outlined.

Results of the original cyclic salt crystallisation test (1984)

The cyclic salt test and subsequent interpretation was performed on 34 sandstone specimens. The results of the test were quantified by taking the percentage volume (V) lost from each specimen after ten cycles of salt crystallisation as a measure of each specimen's durability. The effective porosity (P), dry Point Load Strength Index (S) and swelling clay content (C) of each specimen were also determined, these being the three parameters which the writer considered (in 1984) to play the major role in determining a sandstone's susceptibility to most decay processes.

Regression analysis was performed to test the correlation between the volume % loss (V) and the three measured sandstone properties P, S and C, both individually and in various combinations.

The correlations obtained were expressed in terms of the figure ($100r^2$), which is the degree to which variation in one of the parameters correlates with variation in the other parameter, where "r" is the correlation co-efficient determined by the regression analysis. In these terms, where $100r^2 = 100\%$, the correlation is a completely linear relationship, while a result of $100r^2 = 0\%$ would mean that no correlation whatsoever existed.

The volume % loss (V) of each specimen was compared to each of the measured properties (P, S, and C) individually, using linear regression lines. The purpose of this was to determine whether any one sandstone property, in isolation, played a major role in determining sandstone durability in the salt test.

The volume % loss was then correlated with various combinations of P, S and C using logarithmic regression lines which were found, by experiment, to fit the data for such combinations significantly better than linear correlations. It was expected that some combination of P, S and C would yield a better correlation with volume % loss since it was already considered, on theoretical grounds, that stone durability would be controlled by an interplay of several stone properties, rather than just a single overwhelmingly important property.

The correlations obtained are listed in Table 6.1 below:

RELATIONSHIP	REGRESSION LINE	DEGREE OF CORRELATION ($100r^2$)
V <u>vs</u> C	Linear	5.25%
V <u>vs</u> P	Linear	12.95%
V <u>vs</u> S	Linear	22.85%
V <u>vs</u> S/C	Logarithmic	8.25%
V <u>vs</u> S/P	Logarithmic	45.0%
V <u>vs</u> S/P+C	Logarithmic	45.6%
V <u>vs</u> 1/P+C	Logarithmic	0.0004%

Where: V = Vol. % loss from specimen after 10 salt crystallisation cycles
P = Effective Porosity (Vol. %)
S = Dry Point Load Strength Index (MPa)
C = Swelling Clay content (Vol. % of total sandstone mineral matter)

Table 6.1 Correlation of sandstone durability in the cyclic salt test with measured sandstone properties.

It is clear that none of the three measured sandstone properties, taken in isolation, correlates sufficiently well with durability to be taken as a sole predictor thereof. Strength (S) taken alone provides the best correlation (22.85%), but this is too low to be useful as a predictor of durability.

Since the process of salt attack requires that salt solutions be able to enter sandstone and crystallise in pore spaces, it can be theoretically expected that increasing porosity (P) will have an inverse correlation with increasing stone durability in response to salt attack. Conversely, since the tensile strength of sandstone (\approx Point Load Strength Index (S), see Chapter Two) is a measure of sandstones ability to resist the tensile stresses imposed on

intergranular bonds by salt crystallisation in the pore spaces, it can also be theoretically expected that increasing stone strength will be directly correlated with increasing stone durability in response to salt attack. See the discussion of salt attack processes in Section (5.3.8).

Combining these two considerations, it can be expected that the relationship (S/P) would show a significant correlation with stone volume % loss (V) in the salt test. The correlation found was 45.0% (see Fig. 6.2).

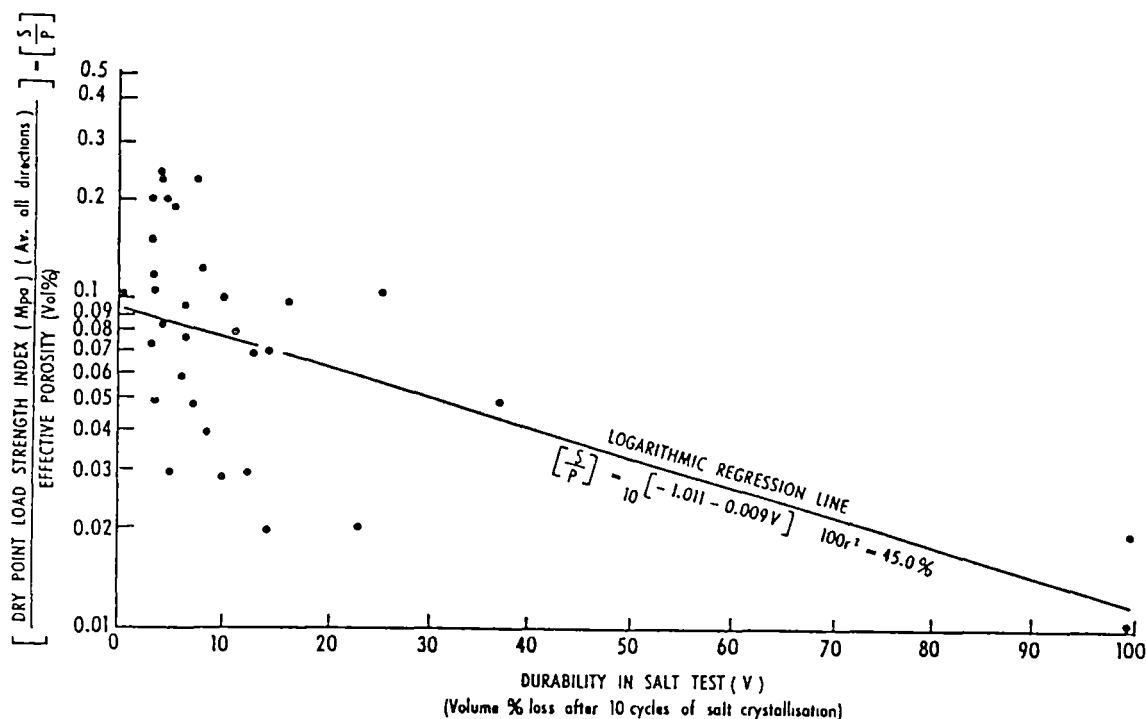


Figure 6.2 Relationship between Durability (in the cyclic NaCl salt test) and Strength/Porosity (S/P) for 34 Tasmanian building sandstone specimens. (Copy of Fig. (B:5.3.3)a of Sharples *et al.* 1984; see also Appendix Seven)

The remaining relationships tested (Table 6.1) constitute an attempt to gauge the contribution of swelling clay content (C) in determining the susceptibility of sandstone to cyclic salt attack. The presence of swelling clay could be expected to enhance the effectiveness of salt attack, by creating an additional stress (the swelling of the clays) during the soaking of the stone in the salt solution. Thus, increasing swelling clay content should be inversely proportional to increasing durability.

However, the results of the regression analysis indicate that any contribution which swelling clays might make to the cyclic salt decay process is trivial. Considering swelling clay content in combination with strength alone (S/C) and in combination with porosity alone (1/P+C), the correlation with volume % loss in the salt test is very low (8.25% and 0.0004% respectively). This indicates that a meaningful correlation of durability with stone properties must take both strength and porosity into account.

Adding the detrimental effect of swelling clays to the more successful relationship (S/P), the correlation between this relationship (S/P+C) and volume % loss is 45.6% - a trivial

0.6% improvement in the correlation compared with the simple relationship (S/P).

Two significant conclusions can be drawn from this analysis:

- 1) There is a significant correlation between sandstone durability in the cyclic salt test and the combined effects of stone strength and porosity, as is expected on theoretical grounds. It is noteworthy that Spry (1983,p.61) has suggested a similar relationship as a predictor of durability (namely, compressive strength/water absorption).

Although the correlation obtained (45%) is still not an especially close one, it is probable that it would be considerably enhanced if porosity and strength were both multiplied by suitable constants:

To suggest that the relationship (S/P) should be directly correlated with volume % loss (ie, durability) in the salt test implies that each further MegaPascal of a stones Point Load Strength Index will increase the stones resistance to salt attack to the same degree that each 1.0% of increasing effective porosity will increase the stones susceptibility to it. It is of course highly unlikely that such a simplistic relationship would hold true.

A more valid equation relating sandstones porosity and strength to its durability in the salt test would take the form:

$$D = a.S/b.P$$

Where:

- D = Sandstone durability, such that increasing values of D imply increasing stone durability (or decreasing vol.% loss in the salt test).
- S = Sandstone strength (tensile strength, or a correlated parameter such as dry Point Load Strength Index)
- P = Sandstone porosity (eg, effective porosity)
- a, b = Constants of proportionality

It would be necessary to determine the constants of proportionality (a & b) through continued laboratory testing and statistical analysis to determine constants giving the best fit to the data.

- 2) The statistical analysis shows no significant effect of the presence of swelling clays on the durability of sandstone when exposed to the conditions of the cyclic salt test. However, it is considered on other grounds (see Section 5.3.9) that swelling clay content does in fact have a significant effect on sandstone durability in the building environment.

It is probable that the cyclic salt test provides a reasonable, if greatly accelerated, reproduction of the effects of actual salt attack on sandstone in the building environment. At the same time, it is likely that decay through wet/dry expansion/contraction cycling of swelling clays is a process which is not amenable to simulation through an accelerated stress test.

The continuing growth of salt crystals in sandstone pore spaces between the soaking cycles of the salt crystallisation test may produce a progressively increasing strain on sandstone intergranular bonds, which combined with expansion and contraction of the salt in hot/cold cycling can lead to the bonds failing after only a few cycles (in weak

stone).

In contrast, the swelling of smectite clay during soaking cycles produces a strain on the bonds which is relieved inbetween the soaking cycles, and which does not become greater with repeated cycling. As a result, the swelling of the smectite only produces intergranular bond failure after a sufficiently large number of cycles have occurred to induce brittle fatigue failure. Since the number of cycles necessary to produce such failure is not achieved in the standard 10 - 15 cycle laboratory salt tests, failure through swelling clay expansion is not a significant factor in such tests.

Thus, it can be concluded that whilst accelerated decay tests such as the cyclic salt test may give an indication of the likely durability of sandstone in response to salt attack, they do not give a direct indication of the stones susceptibility to other decay processes such as expansion/contraction cycling of swelling clays. Accelerated decay tests do not even give any indication of whether or not swelling clays are present in the stone; and yet such information is clearly indispensable for a proper assessment of durability.

Accelerated decay tests may, on the other hand, give an indirect measure of susceptibility to other decay processes insofar as the test results are to some extent correlated with strength and porosity which, on theoretical grounds, are also considered to exert some control on the smectite expansion/contraction decay process.

However, in order to judge a sandstones susceptibility to swelling clay-related decay, it is also necessary to actually measure the amount of swelling clay present in the stone, and its distribution with respect to the intergranular texture. This information is not yielded by accelerated decay tests, and can only be obtained through mineralogical and petrographic analysis.

Therefore, accelerated decay tests cannot be used in isolation to give a reliable assessment of the durability of sandstone in response to the complex suite of decay processes likely to be experienced in the building environment.

Notwithstanding that there are significant deficiencies (see discussion below) in the cyclic salt test as conducted and analysed in 1984, the writer considers that those deficiencies are not so great as to totally invalidate the two major conclusions above. However, in order to consider these conclusions to be properly established, it will be necessary to repeat the above testing and analysis with the deficiencies in the procedure remedied.

Deficiencies of the original cyclic salt crystallisation test (1984)

Subsequent to completion of the cyclic salt crystallisation tests and analysis (1984), the following deficiencies in the procedures followed have become apparent:

- 1) The distribution of the data points used in the analysis is rather uneven; examination of the figures in Appendix Seven (and see Fig. 6.2 above) shows that most of the samples tested were of either high or low durability, with very few intermediate examples. Since this is likely to produce some distortion of the results, a testing program involving a larger number of samples having a broader range of durabilities would be desirable.
- 2) The content of swelling clay in each sample was calculated using a simplistic technique (Sharples *et al.* 1984,p.243-246), which the writer has now superseded with the technique described in Appendix Three of this thesis. While the differences in results

obtained by each method are small, the use of the updated technique is preferable.

- 3) In the 1984 tests, vermiculite was included amongst the detrimental swelling clays. It is now considered inappropriate to include vermiculite, since it does not display swelling behaviour under normal atmospheric conditions (see Section 2.2.4 D). However, only a few of the samples tested in 1984 actually contained vermiculite, so the results are not greatly distorted due to this factor.
- 4) It may be too simplistic to consider porosity simply in terms of effective porosity. Pore size distribution is considered to play a significant role in determining the susceptibility of sandstone to salt attack, with finer pores being very important (J.Heiman, *pers. comm.* to P. Spratt, 1985). It would be more useful to find a way of determining pore size distribution, and incorporating this information into the analysis in addition to simple effective porosity.
- 5) Similarly, analysing the data in terms of simple dry Point Load Strength Index is also too simplistic, since it does not allow for the influence of intergranular texture in determining such properties as a stones loss of strength with soaking (if a stone loses a significant proportion of its strength on wetting, this will clearly make it more susceptible to decay under conditions involving soaking by salt solutions).

It would be more valid to analyse salt test data by comparing the results with not only dry strength, but also wet/dry strength ratios, total clay content (all clay types), and the fundamental parameters of intergranular texture which determine such ratios (eg, proportions of Quartz/Quartz and Quartz/Clay intergranular bonds).

- 6) Whilst the expansion and contraction of smectite does not significantly affect the durability of sandstone in the cyclic salt test, it is possible that the presence of smectite affects the durability of stone in the test via a different mechanism: the sodium introduced into the stone during the NaCl cyclic salt test may cause the smectite to begin flocculating. This would produce a rapid breakdown of intergranular clay bonds containing smectite, leading to more rapid decay of the stone than would be the case in the absence of smectite.

This possibility has not been demonstrated in the present work, and some field evidence tends not to support the existence of such a mechanism (see Section 5.3.9)

The idea could be tested by choosing sandstone samples with a high smectite content, and examining the smectite using a scanning electron microscope both before and after subjection of the stone to NaCl solutions. If Na does cause flocculation of smectite, the morphology of smectite masses should show evidence of breakdown following exposure to salt.

This being so, sensitive statistical analysis of cyclic sodium chloride or sodium sulphate salt test results should indicate increased salt attack decay in high-smectite sandstones, as compared to high-clay (non-smectite) sandstones. However, the results of the 1984 salt tests suggest that any such smectite-related enhancement of the salt attack process is likely to be relatively minor compared to the gross effects of physical disintegration caused purely by salt crystal expansion.

- 7) The correlation obtained between durability in the salt test and strength/porosity, while clearly significant (at 45%), still accounts for less than half of the variation observed in the results. In order to be able to say that the major factors controlling

durability in the salt test have been identified, it would be necessary to obtain a correlation well in excess of 50%.

It is anticipated that a much better correlation would be achieved if all the deficiencies outlined above were rectified, and if suitable proportionality constants could be determined for the equation ($D = a.S/b.P$), as discussed above. Should such improvements in technique not yield a correlation significantly closer to 100% than obtained to date, the clear conclusion would be that some significant aspects of the salt attack process have still not been addressed by the method used to interpret the salt test results.

Outline of proposed improved testing program

Whilst the sodium chloride cyclic salt crystallisation test, as conducted in 1984 to produce the results analysed above, is a valid accelerated decay test, it would probably be more useful to repeat the program of testing and statistical analysis using the sodium sulphate soundness test, since the latter test is in more general use as a means of assessing sandstone durability.

A large number of samples (50+) should be selected from sandstones expected to have a wide range of durabilities. For each sample, laboratory tests should be conducted to determine mineralogy (vol. % of each mineral type), including clay mineralogy. Intergranular texture, effective porosity, pore size distribution and strength (dry, wet, wet/dry ratio) should be determined.

The samples should be subjected to the standard sodium sulphate soundness test, the results being recorded as a measure of durability. The durabilities should be compared statistically with the above measured properties. By first comparing durabilities with individual properties, it can be determined which properties show the greatest correlations with durability. Such properties can be combined in equations designed to reflect the influence which each is theoretically expected to have on salt decay, as was done in the 1984 test.

The combinations should be experimentally manipulated to determine proportionality constants which will produce the best correlations with observed durability. Since this involves multi-variate analysis, it will probably be necessary to design a computer program to systematically manipulate the data in all possible combinations, so as to come up with proportionality constants which best fit the data.

The data should finally be statistically analysed to determine whether the best correlations obtained are indeed statistically significant (considering the number of data points and the standard deviation). If they are not, it will be necessary to go back to first principles and reconsider the theoretical basis on which sandstone properties were chosen for correlation with observed durability.

6.4 ACTUAL STONE BEHAVIOUR IN BUILDINGS

The observation of actual stone performance in buildings is probably the most reliable means available of assessing stone durability, since it shows how stone has actually performed in response to the actual decay processes operating in the building environment over long periods of time.

However, this method too has a number of major drawbacks:

- 1) Most obviously, the method can only be applied to sandstone from quarries which have been in operation for a considerable period of time. Except in the case of an especially low-durability stone, which might start to show signs of decay within only a few years, it is necessary to observe stone in buildings at least a few decades old in order to determine the durability of the stone over the intended lifespan of a new building.

Of the currently operating Tasmanian sandstone quarries, the only ones with a long history of past usage are the Linden, Oatlands, Nunamara and Pontville White Sandstone quarries. For these quarries, it is indeed very useful to observe the condition of stone which has been in use in buildings for periods of sometimes up to 100 years or more.

The durability of sandstone in prospective but undeveloped outcrops, or quarried from recently opened quarries, can only be assessed by a combination of measuring relevant stone properties and subjecting samples to accelerated decay testing. While some indication of likely durability may sometimes be obtained from observation of similar stones which have been used in the past, this method will not be very reliable since it would be very rare indeed for stone from two different sources to have an identical suite of technical properties.

- 2) The observed durability of sandstone in a building can only be taken to be indicative of the performance of that stone type in the particular environment, and subject to the particular stresses, in which it has actually been used.

Thus, although a particular stone type may have decayed badly in a high stress location within an old building, this does not mean that the stone could not be successfully used in a lower stress environment. Conversely, stone which has performed well for years in a low stress environment is not necessarily suitable for use in high stress applications.

For instance, observation of Linden quarry sandstone in the Hobart G.P.O. (1901) has shown that, due to its smectite content, it tends to develop horizontal cracks over a period of eighty years or less when used in situations such as horizontal ledges where rainwater may pool and soak in (Spratt 1982b). However, it is still likely to perform well in smooth vertical ashlar walls where rainwater can run off quickly (such as its more recent use in the Hobart Supreme Court). This conclusion is indeed supported by observation of the Hobart G.P.O., in which Linden stone in vertical walls is still in good condition.

When stone taken from an old quarry source is used in an environment to which it has not previously been subject, observation of its past performance in different environments may be of little value in predicting its durability. One illustration of this, not particularly applicable to Tasmania but relevant in some other parts of the world, is the effect of modern atmospheric pollution on stonework. Amoroso & Fassina (1983) give examples of European buildings whose stone performed well for hundreds

of years in an unpolluted environment, but then began to decay rapidly during the twentieth century as a result of the marked increase in atmospheric pollutants such as sulphuric acid.

- 3) Observation of stone performance in existing buildings is generally subjective, so that it is difficult to use such observations to put concrete figures on the period of time for which a stone will perform adequately in future use, to quantify the degree of decay which can be expected in particular circumstances, or to define design parameters which should be incorporated into the construction of new buildings to guard against premature failure.

The subjective nature of observations of decay in buildings also means that it is difficult to quantitatively relate the decay observed in a building to the measured physical and mineralogical properties of the sandstone.

6.4.1 Quantification of observed decay, and its relation to sandstone physical properties

It would be of great value to be able to derive quantitative relationships between the actual degree of observed sandstone decay, and the measured values of the physical properties of the sandstone types whose decay (or lack thereof) is observed. If this could be done, it would be possible to approach the goal of predicting stone durability, in a quantitative way, from direct measurements of the stone properties controlling the stones response to decay processes.

The analysis of the cyclic salt test described in Section (6.3.1) was an attempt to quantitatively relate accelerated decay test results to the actual properties of the tested sandstones; the ability to relate stone decay in buildings to sandstone properties would be much more useful since it would be relating stone properties to actual decay processes in the building environment, rather than simply to decay resulting from an artificial and simplistic testing procedure.

Establishing reliable correlations between stone properties and observed decay would involve a complex multi-variate analysis since, as discussed in the above sections, there is no one-to-one relationship between particular stone properties and stone response to particular decay processes. It is possible that such an analysis would become too complex to be of practical value. However, such a conclusion cannot be drawn until the analysis has been attempted! In any case, even if a finely detailed correlation cannot be established, it would be useful to be able to draw relatively broad quantitative correlations between dominant sandstone properties and major decay processes.

In attempting to establish a correlation between measured stone properties and observed stone performance, a multi-variate analysis would be required to correlate all the following factors:

- 1) The interactive effects (see Section 6.2 (1) above) of the suite of sandstone properties measured on fresh sandstone samples considered to be identical to the sandstone observed in buildings.
- 2) The period of time for which the sandstone in the observed buildings has been exposed to decay processes.
- 3) The type and intensity of the decay processes operating on the sandstones in the building (see Section 6.2 (2) above). This would involve quantification of the type and

degree of observed decay, and of the nature of the particular micro- and macro-environments to which the sandstones are exposed (see Section 5.4.4 & 5.4.5).

Because of the multiple variables involved in the proposed analysis, it will be necessary to collect a very large body of data, having a wide spread of values for each variable involved, in order for the correlations derived from this work to be statistically significant. The multi-variate analysis of such a large body of data will probably only be feasible if a computer program is designed for the purpose.

6.5 CONCLUSIONS: OPTIMUM ASSESSMENT OF SANDSTONE DURABILITY

The assessment of sandstone durability in the building environment remains an essentially qualitative process, although the collection of quantitative data is an essential part of the process. Data on sandstone properties, accelerated decay testing and actual stone performance in buildings is all useful and important, but each of these types of data is subject to limitations.

Optimum assessments of durability are made by interpreting a combination of data from all three sources in the light of an understanding of the nature of sandstone properties, and of the processes of sandstone decay.

CHAPTER SEVEN

GEOLOGICAL CONTROLS ON QUALITY AND DURABILITY-RELATED SANDSTONE PROPERTIES

7.1 PURPOSE OF CHAPTER

Previous chapters have presented arguments and data to establish which properties control the durability of sandstone in the building environment. Additionally, other properties have been mentioned which, while not necessarily controlling durability, nevertheless determine ease of quarrying, workability and aesthetic appearance, all of which are relevant to deciding upon the suitability of stone for building purposes.

The purpose of this chapter is to discuss the genesis of these properties.

In the past, the identification of useful sandstone sources seems to have occurred in an almost random fashion. Interesting outcrops have been found more or less by chance (for example, the Molesworth sandstone (Source 29) was stumbled across during a rabbit shooting trip!). Literally dozens of quarries have been opened on such outcrops; in a few cases good stone has been extracted, but in many more cases only mediocre stone has been obtained.

Today, the science and technology of stone use has progressed to a stage where the use of poor or mediocre stone is no longer acceptable. Stringent quality standards now play a major role in stone supply contracts, and it is becoming clear that many existing quarries do not come up to standard. There is a need to locate new sources of high quality, durable stone.

The old "random chance" methods of locating sandstone sources no longer suffice. The stone industry needs to follow the lead of the mineral industry: that of acquiring the means to explore in a systematic fashion, using geological knowledge to narrow down the most prospective areas so as to give the best chance of locating high quality stone sources by efficient means.

In order to do this, we require as much information as possible on the geological environments which give rise to the occurrence of good building sandstones; that is, we need data on the depositional, diagenetic, tectonic and weathering environments which tend to produce stone having the preferred properties.

This chapter discusses the knowledge (and speculations) acquired to date on the geological controls on the genesis of the relevant properties in Tasmanian sandstones.

The information and speculations incorporated in this chapter have been variously derived (as indicated in the text) from study of existing literature, and from investigations conducted during this project.

7.2 PROPERTIES DETERMINING QUALITY AND DURABILITY OF SANDSTONES

The following is a concise listing of the properties previously argued to be of greatest importance in determining sandstone quality and durability. Since this chapter is intended as an initial attempt to produce guidelines for effective sandstone exploration, for completeness some important preliminary field criteria of a non-geological nature are also listed:

FIELD OR MACROSCOPIC CRITERIA

- | | |
|--|--|
| Suitability of site | - Landowner agreeable? |
| | - Environmental considerations acceptable? |
| | - Access for machinery? |
| | - Overburden minimal? |
| | - Slope angle and topography acceptable? |
| | - Sufficient extractable reserves? |
| Joint/fracture spacing wide enough? | |
| Bedding suitable? | - Type and thickness |
| | - Dip angle |
| Colour and colour patterning suitable? | |
| Sedimentary texture aesthetically acceptable? | |
| Defects minimal? (Pebbles, clay pellets, porous spots, concretions, mudbands, etc) | |

LABORATORY OR MICROSCOPIC CRITERIA

- | | |
|-----------------------------|--|
| Mineralogy | -Chemically and physically stable?
(quartz, clay, deleterious minerals %) |
| Strength | - High enough? High wet/dry ratio? |
| Porosity (Water absorption) | - Low enough? |
| Bulk Density | - High enough? |
| Dimensional Stability | - Good enough? |

As will become apparent, strength, dimensional stability, porosity and density are simply the "net" result of a range of more fundamental intergranular textural and mineralogical properties.

Following sections discuss each of these listed criteria in detail:

7.3 SUITABILITY OF SITE

(A) Landowner agreeable?

There is little point in attempting to open a quarry on private land unless the landowner is happy about it. It is important to consider the likely effect of quarry operations on the owners livelihood and assets, and to negotiate acceptable royalty payments.

(B) Environmental considerations

Possible problems include visual impact of quarry from roads or houses, noise, vibration or dust emissions, damage to vegetation and crops, silting of watercourses, and interference with stock and other animals.

(C) Access for machinery?

Few quarry operators can afford to construct access roads over long distances or across difficult terrain. Potential quarry sites must be either already serviced by usable vehicular

tracks, or else be accessible across easy ground.

(D) Topography, slope angle, overburden and reserves

It is usually uneconomical to remove more than a few metres of overburden (soil, unsuitable stone) from above a bed of saleable stone. It is also necessary to be able to form a flat platform at the base and/or top of the outcrop face upon which to commence working the face.

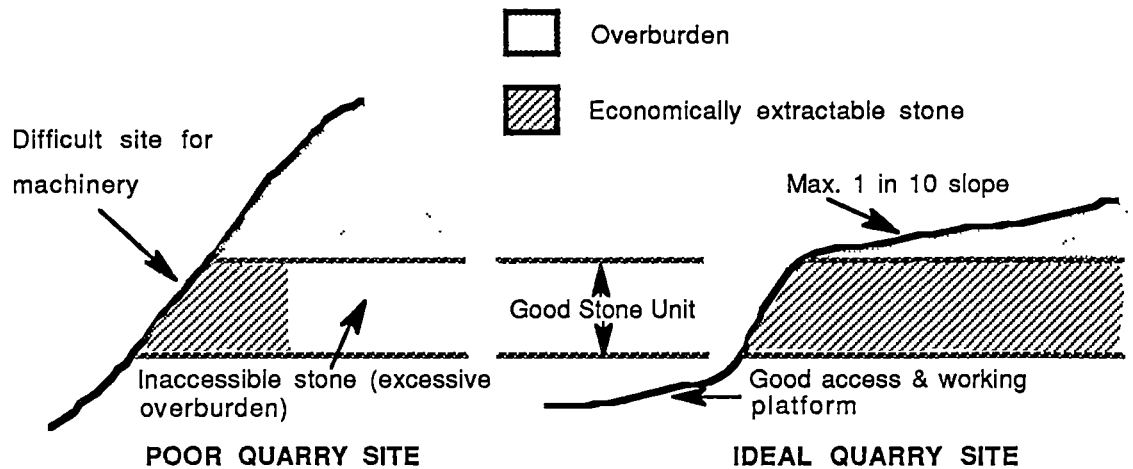


Figure 7.1 The importance of topography in choosing quarry sites.

In long term quarry operations the normal method employed is to work back into the sandstone face on horizontal benches with working faces ideally about four metres high. There needs to be sufficient good stone extractable in this fashion to last for the anticipated life of the quarry.

The ideal quarry site would begin from an outcropping face of good stone, with minimal overburden and with horizontal or gently sloping ground below, and running back above the face for a considerable distance. A rising slope gradient above the face of 1 in 10 is ideally the steepest slope angle which will allow quarry benches to extend back far enough for economical stone extraction on four metre faces. A higher slope angle means shorter benches, and thus new benches must be commenced more often, resulting in higher operating costs. See Figure (7.1).

7.4 JOINT AND FRACTURE SPACING

Joints (or fractures) must generally be spaced at least two metres apart (preferably more) to allow extraction of unflawed sandstone blocks large enough to be used. Exceptions to this rule exist, however; for instance, the Cobbs Hill quarry has closely spaced fractures, but is successfully operated to produce small dimension blocks for domestic use.

7.4.1 Controls on joint and fracture spacing

Jointing and deep fracturing are caused by tectonic (including epeirogenic) stresses, and intrusive or unloading processes.

Joint and fracture spacings in a rock mass affected by these causes are controlled by a number of intrinsic and environmental properties of the rock mass. The intrinsic properties include composition, grain size, porosity and permeability, and bed thickness. Relevant environmental properties include the overburdens, temperatures, differential stresses, strain rates and pore fluid compositions to which the rock has been subject during its burial and uplift history (Friedman *et al.* 1986, Aguilera 1988).

Jointing

Jointing (as defined in Chapter Two) is normally of greater importance in Tasmanian building sandstones than fracturing. The following observations can be made about factors controlling joint spacing ("frequency", "intensity" or "density") in sandstones, with particular reference to Tasmania:

(A) Tectonic stresses - Faulting

Tectonic stresses may produce folding, faulting and jointing. Folding deformation itself produces jointing, but is probably of little relevance to Tasmanian Permian or Triassic sandstones which in most areas are undeformed and only slightly tilted.

However, tectonic stresses have produced major faulting in the Tasmania Basin, containing the sandstones of the Parmeener Supergroup. Since it is probable that faulting and jointing are genetically related to each other, their densities should be proportional.

It is known (Legge 1967) that closely spaced joints may occur near faults, and Leaman (1971, p.35) showed that there are commonly large numbers of small joints associated with Mesozoic faults in competent rocks in SE Tasmania.

Individual faults seem to generally produce significant localised increases in joint density within only five metres or so of the faults, although the effect will extend further in stronger and more brittle sandstones.

An excellent example of the relationship of jointing to individual faults occurs in the Nunamara Quarry (Source 25), where a normal fault occurs at the eastern end of the main face. The fault is downthrown six metres towards the east, and the sandstone is intensely shattered and closely jointed parallel to the fault for approximately 7.0 metres west of the fault. Further than seven metres west of the fault, however, the intense jointing abruptly ceases and is replaced by the wider regional joint spacings typical of the rest of the quarry.

Similarly, the moderate strength sandstone at the Elderslie quarry (Source 26) occurs within only 120 metres of a major fault, yet is widely jointed and generally free of deep fractures.

The important relationship between faulting and jointing is found on a more regional scale; that is, the average joint density over reasonably large areas is related to the regional

density or intensity of faulting over the entire area (regional fault and joint densities both being related primarily to the intensity of the regional stress field which formed them).

Thus, over a large area ("large" meaning perhaps some tens or hundreds of square kilometres?) with a low density of faulting, it could be expected that there would in most places be a relatively low joint density, with only localised increases in joint density immediately adjacent to such faults as do occur. In an area of high overall fault density, joint density could be expected to be high both close to and away from faults.

Observations made to date appear to support this assertion (see Fig. 7.3). Joint density in Early Triassic sandstones is generally high in the Hobart - New Norfolk region, which is within the intensely faulted Tertiary Derwent Graben (see Plate 7.1). On the other hand, Early Triassic sandstones in nearby regions of comparatively low fault density, including the Oatlands and Elderslie regions, have predominantly widely spaced joints. An investigation to quantitatively test the validity of these observations is proposed in Section (7.4.2).

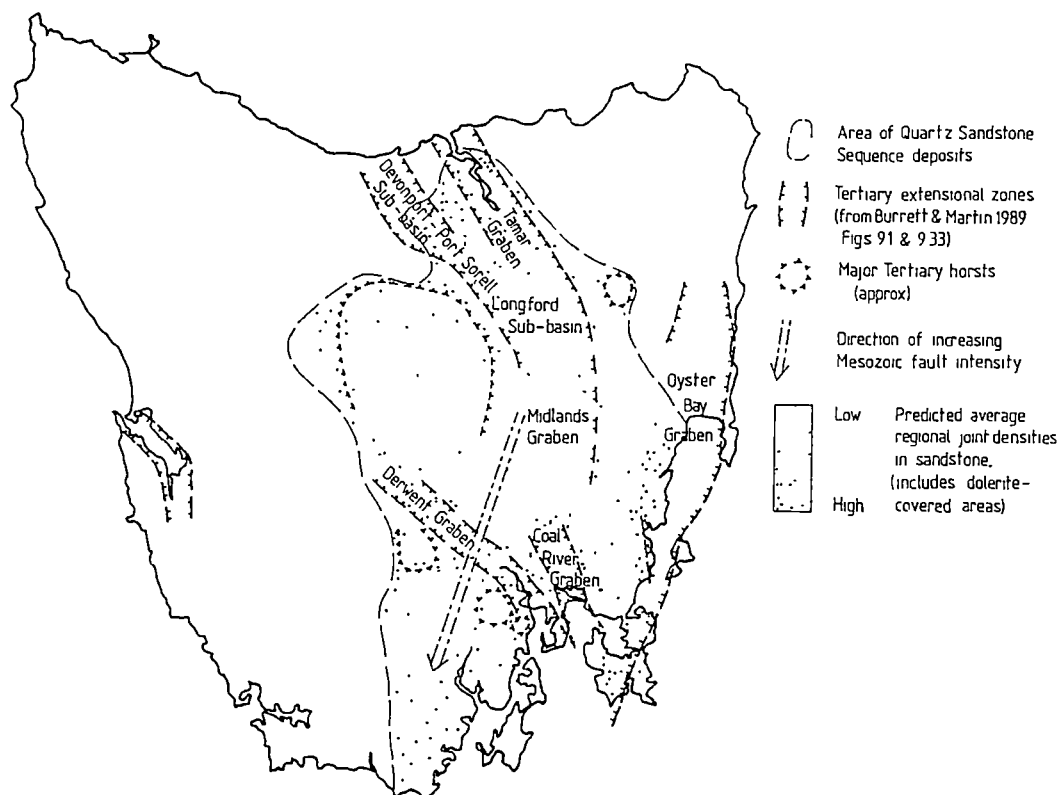


Figure 7.2 Predicted regional variation in Mesozoic and Tertiary fault and joint densities in the Tasmania Basin. Interpretation partly based on work by R.F.Berry (Publication *in prep.*).

Berry & Banks (1985) found that much of the faulting in the Parmeener Supergroup of south-eastern Tasmania could be related to at least two major tectonic episodes:

A major NNW compressional event in the Mesozoic (active before and after intrusion of dolerite in the Jurassic) established a wrench faulting pattern with strike slip faults striking 100 degrees and 170 degrees, and reverse faults striking NE. A subsequent phase of Early to Middle Tertiary normal faulting produced a horst and graben system, including the Derwent graben, by E to NE extension, involving re-activation of earlier faults striking 170 degrees. Finally, a Late Tertiary phase of strike slip and reverse faulting, related again to NNW compression, may have affected faults in the Hobart region.

Continuing work (R.F.Berry, *pers.comm.* 1990, publication *in prep.*) has shown that regional variations occur in the intensity of the faulting related to these events. This work is leading to an ability to predict likely average regional jointing intensities in various parts Tasmania.

Berry has found that the Mesozoic faulting is most intense in southernmost and western Tasmania, and decreases in intensity north of Hobart. The least intense Mesozoic faulting occurs in the northeast, from the Lake Leake area northwards (See Fig. 7.2).

Berry has measured the Mesozoic faulting in the stronger and more brittle Jurassic dolerites, in which the faulting is well expressed. While the Mesozoic faulting (and associated jointing) can be expected to be less intense in the weaker and more elastic Parmeener Supergroup sandstones, the same general pattern of decreasing fault and joint intensity can be expected towards the northeast.

The Tertiary horst and graben faulting is (naturally) most intense within the major horst and graben structures, including the Derwent and Tamar grabens, and the Ben Lomond, Central Plateau, Mt. Field, Mt. Dromedary and Mt. Wellington horst blocks (Colhoun, *in* Burrett & Martin 1989,p.405). Tertiary faulting associated with the opening of the Tasman Sea is also quite intense along the east coast (Oyster Bay Graben, see Fig. 7.2).

The jointing associated with Tertiary faulting seems to have had less effect on the dolerites than did the Mesozoic faulting, since the present writer has observed widely-jointed dolerites in the Launceston region, despite the intense Tertiary faulting present within the Tamar Graben. This may be because the Tertiary tectonic stresses were largely absorbed by the pre-existing Mesozoic tectonic (and cooling) joints already present in the dolerite.

In regard to the sandstones, by combining the effects of Mesozoic and Tertiary faulting one would expect the widest joint spacings to occur in the northeast, in outcrops outside the Tertiary horst and graben zones. Interestingly, very widely spaced jointing has been noted by the writer in outcrops of the Quartz Sandstone Sequence near Blessington (see Fig. 7.3), which is situated in the northeast between the Tamar Graben and the Ben Lomond Horst (Grid Ref. EQ393009). This is one of only a very few areas in the northeast where the Quartz Sandstone Sequence is not covered by Jurassic dolerite sheets.

Data collected during this project (see Fig. 7.3) indicates that, in general, the Tertiary faulting had a much stronger effect on jointing in the sandstones than the Mesozoic faulting did. Thus, as noted above, sandstones within the Derwent Graben have a generally high density of faulting and jointing while sandstones just north of the graben (in the Elderslie - Melton Mowbray region) are less faulted and are much more widely jointed. Some sandstone deposits south of the Derwent Graben are also widely jointed.

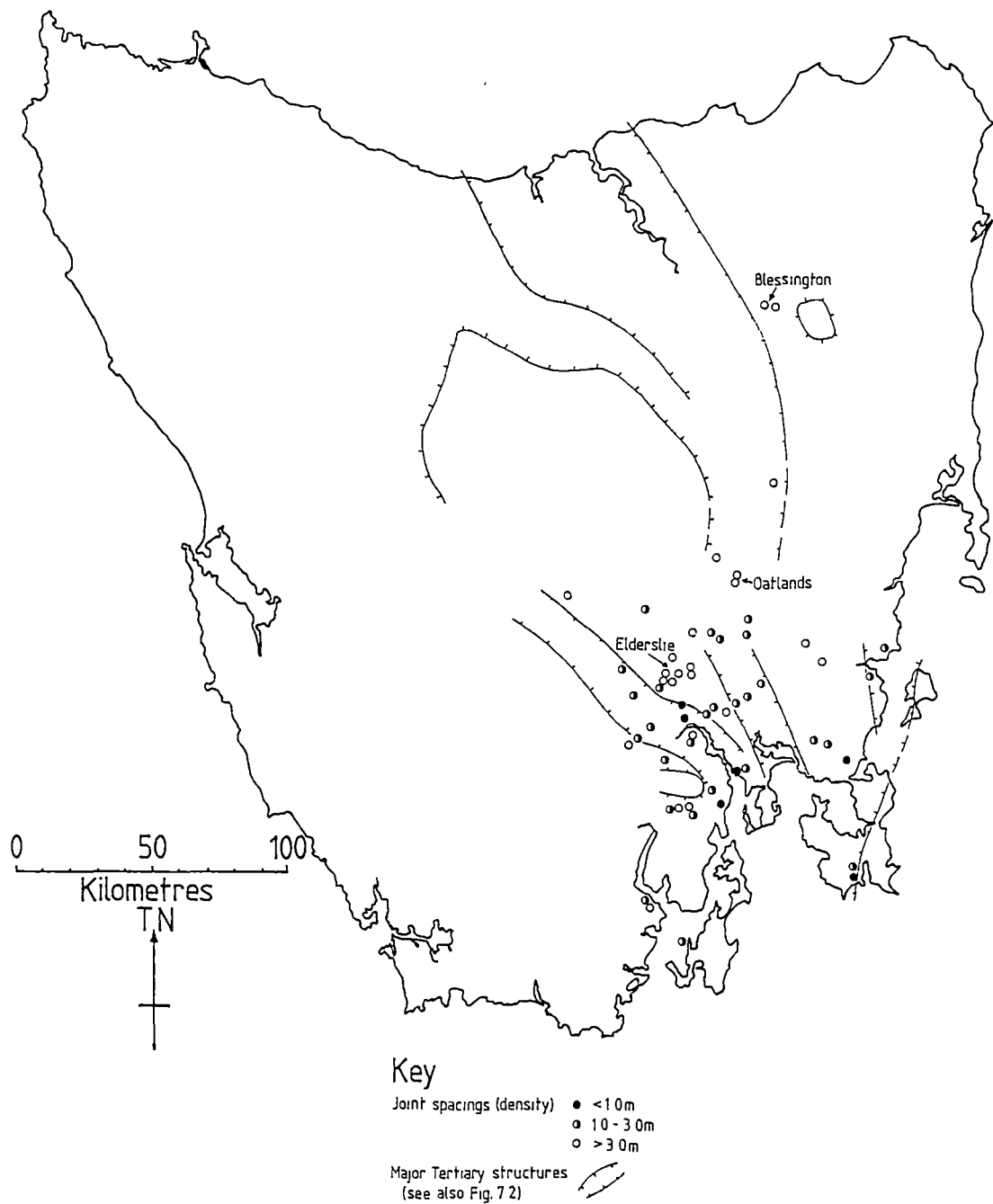


Figure 7.3 Actual joint spacings measured in quarries and outcrop sites in the Quartz Sandstone Sequence during this project (see Appendix Ten). Compare with predicted joint densities in Fig. 7.2.

It is possible that increased heat flow associated with the extensional development of the Tertiary grabens strengthened the sandstones within them (through increased silica bonding; see Section 7.9.1), thereby making them more brittle and susceptible to jointing within the grabens (see also Section 7.4.1 E). In contrast, during the Mesozoic the sandstones throughout the Tasmania Basin would have generally been somewhat weaker and more elastic, having only been subject to normal burial-related silica cementation without the addition of further Tertiary cementation in the grabens.

Thus, although the sandstones were sufficiently brittle by Jurassic times to experience significant faulting (see Leaman 1975), they nonetheless still retained sufficient elasticity to escape being jointed as intensely as would later occur in the Tertiary.

The net effect of this is that sandstones sufficiently widely jointed to be quarried for building stone can be expected to occur throughout the Tasmania Basin, except in the areas affected by intense Tertiary faulting.



Plate 7.1 Closely spaced sub-parallel jointing within the Tertiary Derwent Graben. Linden Quarry (Source 27).

(B) Igneous intrusions

Joint densities increase close to intrusive contacts, and joints are often sub-parallel or sub-perpendicular to contacts, implying a genetic relationship (Legge 1967, Green 1961). Leaman (1971) found this effect in the contact zone of dolerites in SE Tasmania. The effect can be attributed both to physical movement associated with the intrusion event, and to tension during the cooling of the dolerite. However, the contact zone of distinctly increased joint density is rarely wider than three to six metres (Leaman 1971).

Leaman found that basalt intrusions usually have a lesser effect on the country rock due to the smaller size of the intrusive dykes and necks, although columnar jointing in sandstone around a basalt neck at Apsley is attributed to contact metamorphic effects (Spry & Solomon 1964)

The degree to which igneous intrusions might have a broader regional affect on joint densities is likely to depend upon the volume of the igneous body (larger bodies implying greater physical disruption of the country rocks), and the degree of heating and cooling experienced by the country rock.

With regard to regional heating and cooling effects on sandstone jointing, wet and slow-cooling magmas would be expected to have a more intense and wide-spread heating/cooling effect on country rocks than dry, rapidly-cooling magmas. Leaman (1975) considered the Jurassic dolerites of the Hobart region to have been a magma of low heat capacity or low in aqueous phases ("dry"). This suggests that any regional-scale jointing resulting from the dolerite intrusions will be primarily related to the physical movement resulting from intrusion of large magma bodies, rather than to heating/cooling effects on the country rocks.

Leaman (1975, p.177,182) asserts that during dolerite intrusion most of the sedimentary column was subject to brittle fracture, and that the magma intrusion occurred by expansion of fractures. The Mesozoic wrench faulting discussed in (A) above spanned the period of the dolerite intrusion, and pre-existing faults or joints were responsible for many of the fractures along which dolerite intruded (Leaman 1975, p.183). The Mesozoic wrench faulting thus probably predominated over any faulting and jointing initiated in the Triassic sandstones purely by the force of the intruding magma mass itself.

(C) Bedding and grainsize

Thicker bedding tends to be related to coarser grainsizes, and both these factors are often associated with more widely spaced joints (Legge 1967, Belousov 1962). It is not uncommon for joint spacings in a single outcrop to vary between beds of differing thickness and grainsize.

(D) Unloading

Unloading generally produces parallel joints which are sub-horizontal or at least parallel to topographic surfaces, and results from the release of stress in rock when overburden is eroded off (Ollier 1969, p.5).

Unloading joint patterns are controlled by the burial and erosional history of the rocks involved. Granites, for instance, may show strong unloading joint patterns because they commonly have been buried at a depth of many kilometres, and so have been relieved of a great deal of overburden pressure upon uplift and erosion.

However, Tasmanian Triassic sandstones appear to have been buried at much shallower depths, probably in the order of one to three kilometres (see Everard *in* Turner & Calver 1987, p.144), with the result that they had comparatively little over-burden pressure to be relieved. Probably for this reason, unloading jointing does not appear very significant in Tasmanian Triassic sandstones, although sub-horizontal breaks along bedding planes are commonly observed and may be at least partly related to unloading.

Such unloading jointing as does occur will be partly controlled by the erosional history and morphology of particular sites and local areas.

(E) Sandstone strength (Intergranular Texture)

As a general rule, stronger (more competent) and more brittle rocks tend to develop greater joint (and fracture) densities in response to a given tectonic stress than do weaker and more elastic rocks. For this reason it is commonly found in Tasmania that the (more rigid) dolerites will show more intense tectonic jointing than the softer sandstones in the same area.

Although the strength differences between Tasmanian Triassic sandstones are less than those between sandstones and dolerites, unusually intense fracturing has been noted in some stronger Tasmanian sandstones close to faults, while softer sandstones near faults may show very little fracturing (see "Deep Fracturing" below).

It appears that high strength stones are more susceptible to jointing and fracturing due to nearby fault movement, since they have high proportions of quartz bonds and are thus less elastic (ie, more brittle). The lower strength stones with more soft plastic clay bonding are more elastic, and may thus be less susceptible to suffering fracturing despite being subjected to similar stresses.

Relatively high heat flow along the extensional Derwent Graben during the Tertiary may have caused slight strengthening of sandstones in the graben, through increased silica bonding by quartz overgrowths (see (A) above, & Section 7.9.1). Thus, the Cobbs Hill, Linden and Molesworth sandstones, all of which fall within the Derwent Graben, are amongst the strongest quarried Tasmanian sandstones.

Since sandstones in the Derwent graben can already be expected to be intensely jointed simply in virtue of the high fault densities in that region, the possibility of the sandstones also being slightly stronger in the graben would imply still more intense jointing than the fault density alone might suggest! A similar situation can be expected in other extensional Tertiary grabens in Tasmania.

Thus we have an annoyingly paradoxical situation that while increased heat flow may produce stronger (and thus more durable) sandstones, that heat flow will commonly be associated with intense extensional fault zones whose continuing movement will then joint and fracture the now-stronger sandstones more intensely than would otherwise have been the case.

Deep fracturing

In regard to irregular deep fracturing of sandstone (as opposed to regular jointing or superficial weathering-related fractures), intense fracturing has been noted in several deposits within a few hundred metres of large faults (eg, Tea Tree Source 13 and Cobbs Hill Source 23 quarries). On the other hand, some deposits (eg, Elderslie Quarry, Source 26) have very little deep fracturing despite occurring very close to faults.

Whilst Tea-Tree stone is of relatively high strength, and Cobbs Hill stone has very high strength, the Elderslie stone is of only moderate strength, and has a high proportion of intergranular clay bonds. This suggests that the degree of fracturing in response to nearby faults is related to the strength and intergranular texture of the sandstone, as discussed above.

Interestingly, the Tea Tree and Cobbs Hill sandstones are within or on the edge of the Derwent and Coal River grabens (higher heat flow leading to more silica bonding?), while the Elderslie stone is north of the Derwent graben in an area which probably experienced lower heat flow resulting in less silica bonding.

7.4.2 Keys to location of widely-jointed sandstones

The above controlling factors indicate possible approaches to predicting regional variations in joint densities.

The most prevalent jointing in Tasmanian Triassic sandstones is steep or sub-vertical jointing which appears to be related to tectonic stresses and faulting as suggested in Section (7.4.1 A) above. There may also be a degree of control on jointing density resulting from major Jurassic dolerite intrusions, although any such control will be largely dominated by the contemporaneous Mesozoic wrench faulting patterns.

The evidence of regional joint density variations related to Mesozoic and Tertiary faulting can be used to roughly predict likely regions of low jointing density in Parmeener Supergroup sandstones (Fig. 7.2). However, further refinement of the data will greatly improve the value of such predictions. Two complementary approaches to such refinement are recommended:

(1) Quantification of relationship between faulting and jointing density

In order to test the validity of, and hopefully quantify, the relationship between faulting and jointing density (and also to investigate whether large dolerite intrusions have a significant effect on jointing patterns), it will be necessary to make detailed measurements of joint densities in a number of "sample" areas of the Early Triassic Quartz Sandstone Sequence having a range of different mapped fault densities and differing amounts and forms of dolerite intrusion.

Sample areas should include areas within Tertiary horsts and grabens, and also a number of areas outside the horsts and grabens, ranging from southern to northeastern Tasmania (ie, encompassing the full range of expected Mesozoic faulting and jointing densities).

It should be noted that prediction of joint density from known fault density (and occurrence of dolerite) cannot be expected to work unless mapping has been sufficiently uniform in quality and methodology to ensure that most faults and intrusions of a given range of sizes (or more precisely, of similar intensity in their effects on the surrounding sandstones) have been located and mapped with a similar degree of confidence in all areas.

Unfortunately, mapping of the Parmeener Supergroup has not yet been completed to such a uniform degree of confidence. It would be necessary to determine a means of defining an appropriate degree of confidence, so that one would be able to specify the reliability of joint density prediction which can be expected in particular areas which have been mapped to particular degrees of confidence.

It will therefore be important to choose sample areas which all have an approximately equal degree of confidence in the mapping of faults. Faulting has been mapped fairly recently and in some detail in the Hobart, Brighton, Kingborough, Oatlands, Interlaken and Sorell quadrangles (Leaman 1972, Leaman *et al.* 1975, Farmer 1981, Forsyth *et al.* 1976, Forsyth 1986, Gulline 1982). For the purposes of the suggested study, faulting can probably be assumed to be mapped to a similar degree of confidence in these regions.

As a procedural matter, in measuring joint densities it will be necessary to allow for the bedding thickness, grainsize and strength or intergranular texture of sandstone outcrops upon which joint spacings are measured, since these factors will cause joint spacing variations independent of the effects of regional faulting (see Sections 7.4.1 C & E). The simplest method may be to only sample outcrops having grain-sizes and bed thicknesses within a standard range.

Joint directions should also be measured, to provide a further test of the relationship of jointing to faulting and dolerite intrusion (by comparing the directions of joints to the directions of supposedly-related faults, and to the morphology of possibly-related dolerite intrusions in a region).

The age of faulting is important, since only faults which have been active subsequent to deposition of the sandstone would be of relevance. Thus, Permian-age faulting in Permian rocks adjacent to Triassic sandstone bodies would not be relevant, unless the faults continued to be active at later times. In fact, most faulting in the Parmeener Supergroup does appear to be of post-Triassic age (See Section 7.4.1. A).

Such a study would allow assessment of the degree to which joint density can in general be correlated with fault density (and dolerite intrusions?). If a clear correlation can be established, joint density would be at least partly predictable in all areas for which faulting (and dolerite intrusions?) have been mapped in sufficient detail. There would still of course be a further degree of localised joint density variation related to grainsize, strength, bed thicknesses, and perhaps to unloading and proximity to particular individual faults and intrusions.

(2) Determination of regional fault density variations through the Tasmania Basin

Having established the degree to which faulting density is related to joint density, if a good correlation exists (as expected) then the next step is to outline in as much detail as possible the known regional variation in faulting density through the Parmeener Supergroup, and in particular the Early Triassic Quartz Sandstone Sequence deposits, of the Tasmania Basin.

Figure 7.2 (see Section 7.4.1 A) is a first order approximation of the variation in fault and joint density which is expected on the basis of current information. In order to improve on this information, a more detailed "joint prediction" map should be prepared showing all known Mesozoic and Tertiary faults in the Tasmania Basin. Such a map should include the horst and graben zones, and all known faulting outside those zones.

Such a map can be prepared using the best geological mapping currently available, but will be subject to the limitation that, as mentioned above, the detail of existing mapping varies considerably between some regions. Comparison of existing mapping with magnetic intensity maps may be of assistance in outlining the intensely faulted Tertiary horst and graben zones in regions where current mapping is not sufficiently detailed for the purpose, or where probable major faults are obscured.

Following preparation of such a predictive map, it should be tested and refined by comparing predicted regional joint densities with actual jointing, as measured at the sample sites chosen in (1) above. Figure (7.3) is an initial test of this sort, using data collected during this project, and appears to give quite good confirmation of the predicted joint densities. Ongoing fieldwork, ideally in the form of a program of systematic field measurements of joint densities throughout the Tasmania Basin, should be conducted to further test and refine the predictive model.

Other keys to location of widely jointed sandstones

The texture requirements for building sandstone (see Section 7.7) place strict limitations on acceptable grainsizes, so that there is little choice in that regard. Coarse grained sandstones may have generally wider jointing, but are rarely considered aesthetically desirable building stone. We are therefore looking for locations where other factors have allowed fine- to medium-grained sandstones to retain wide joint spacings.

Location of thickly bedded sandstones is one indicator of widely jointed sandstones which might be used in a limited way; however there is little evidence of systematic and thus predictable regional (lateral) variations in bedding thickness across the Quartz Sandstone Sequence (see Sections 3.3.2 & 7.5.4). However, there is some evidence of vague systematic stratigraphic (vertical) trends in bedding thickness (see Sections 7.5.2 & 7.5.4), with thicker bedding being more prevalent towards the base of the Quartz Sandstone Sequence.

The best field indicator of widely-jointed (and also thickly bedded) sandstones available at present is simply the size and boldness of outcrops. Higher density of jointing leads to more intense weathering and erosion (Legge 1967, Ollier 1969 p.200, Leaman 1971 p.36-37), although this is less marked in sandstone than in certain other rock types such as granite (Ollier p.75). Large bold outcrops of sandstone are indeed often found to have wider joint spacings than do sandstones in small outcrops or low relief areas.

A point which can complicate exploration is that many sandstone outcrops have small fractures which are only superficial and do not reflect true joint/fracture density within the mass of sandstone. Superficial fractures are generally irregular or polygonal in shape, and are distinguishable from sets of planar parallel fractures which are the superficial expression of joints extending throughout the sandstone body.

(Note that, while closely spaced polygonal surface fractures known as "elephant skin" or "pachydermal" fracturing (see Plate 7.2) do not reflect deep jointing or fracturing in the stone, they may on the other hand indicate dimensional instability; see discussion in Section 7.9.3)

7.5 BEDDING

Sandstone intended for use as large dimension blocks needs to be cut free of internal bedding planes prone to splitting. Thus, such weak splitting planes must be as far apart as possible in the quarry outcrop (generally two metres or more). Internal laminations should be as indistinct as possible to give minimal strength anisotropy. Thick beds of massive sandstone are the ideal, although large-scale cross-bed units with no mica or graphite on the lamination planes could be of adequate quality.

Planar-bedded sandstone with closely spaced splitting planes is usually only appropriate for production of thin slabs and tiles.

7.5.1 Origin of bedform types

Sandstone bedding type is entirely controlled by the environment of deposition. The following discussion concentrates on fluvial depositional environments, since the bulk of Tasmanian building sandstone is derived from Early Triassic deposits which previous work has shown were deposited in fluvial environments (see Chapter Three, and Spry & Banks 1962, Forsyth 1984, 1987 & *in* Burrett & Martin 1989). The Permian Nunamara sandstone (Source 25) is also considered to be a fluvial deposit (see Section 3.2.1).

The type of bedform (bedding) produced by water flow over sand depends on the "flow regime", or degree of stream power, defined as the product of the average water velocity and the shear stress on the stream bed (Blatt *et al.* 1972,p.121), and upon the sediment grainsize and grain shape or hydraulic radius.

Experimental work (Simons & Richardson 1961, and Allen 1968, *in* Blatt *et al.* 1972, p.120-121) showed that varying stream powers will produce bedforms in sands varying as in Figure 7.4 below:

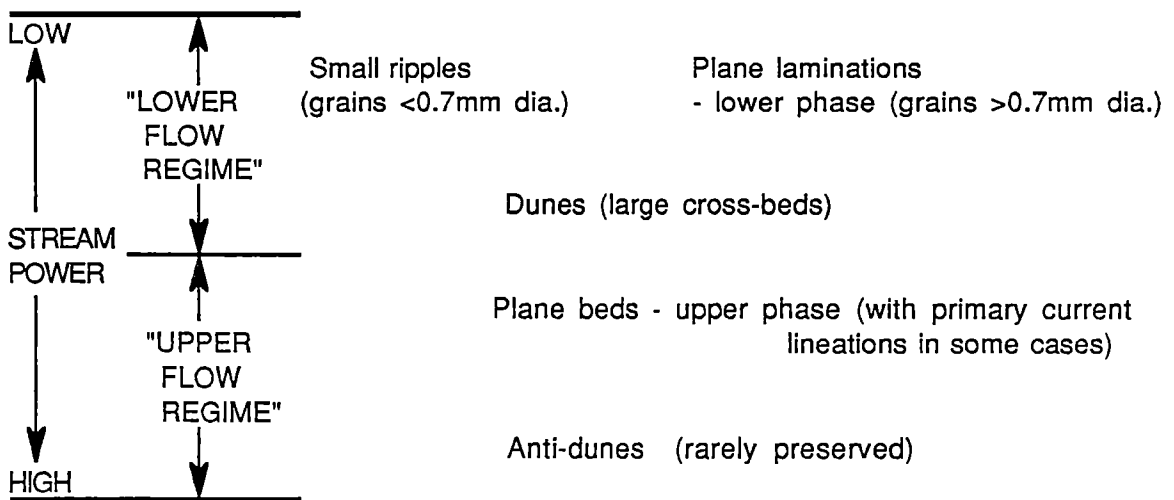


FIGURE 7.4 Relationship of flow regime to bed-forms deposited

At lower stream powers, only silts and clays will be transported and deposited.

Much supposedly "massive" bedding is in fact very faintly plane or cross-bedded, and would thus fit within the above scheme. In the case of true structureless massive beds, it has been suggested (Blatt *et al.* 1972,p.118) that such beds can result either from very rapid deposition from suspension or by deposition from very highly concentrated sediment

dispersions.

In a fluvial environment such deposition could occur during flooding, with high suspended sediment concentrations in upper flow regime floodwaters leading to rapid dumping of the sediment load as the flood wanes. Rapid migration of channels (whether due to flooding or otherwise) would similarly cause a rapid redistribution of sand, resulting in the dumping of large quantities of sand in massive beds as the fluvial system reaches a new equilibrium configuration.

Massive beds formed in such a fashion could be expected to show some fining-up grading. Such grading occurs in some massive beds in Tasmanian Permian (Nunamara Source 25) and Early Triassic sandstones, but is not always observed.

The water flow variations which give rise to bedform variations can be due to short-term or seasonal variations, or can result from gradual changes produced by progressive build-up of sediments in point, braid and channel bars.

Sediment deposition takes place in declining flow regimes (Visser 1972), since increasing flow causes erosion. Much of the sediment deposited in meandering fluvial systems (eg, Nunamara Source 25, see Ch. 3) accretes on point bars. Allen (1982,p.95) described point bars in a sand-bed river as "Lateral Accretion Deposits", in reference to the fact that they accumulate in a lateral fashion as channels migrate.

At any point in time a horizontal traverse across an actively accreting point bar surface will reveal gradually increasing stream power, or flow regime, towards the channel centre. Any vertical section through the bar will reveal a sequence of bedforms reflecting the gradually decreasing flow regimes which have migrated across that specific point as the bar built up and the channel centre moved laterally away.

We can thus expect that in migrating fluvial channels, point bar sediment accumulations would show a typical vertical sequence of bedforms corresponding to that indicated in Fig.(7.4). Variations in the sequence will result from short-term flow rate fluctuations, and abrupt erosional breaks with re-activation of new cycles due to flooding or continuing channel migration encroaching into older deposits.

Such sequences are observed in both ancient and recent fluvial sands (Blatt *et al.* 1972,p.122; Visser 1972), although commonly with certain bedforms missing or replaced by others. Anti-dunes are rarely preserved.

It is possible to propose an "ideal" sequence of bedforms appropriate to sandstones deposited in a meandering fluvial system, although any individual sequence will have variations due to the causes mentioned above.

This "ideal" model applies to sand-size channel (point and channel bar) deposits. Muds, silts and clays are also found in fluvial systems, being laid down in lakes, ponds, levees, floodplains and other over-bank environments. Such lutites are a minor component of Tasmanian Early Triassic sandstone sequences.

The ideal model is illustrated in Fig. 7.5 below:

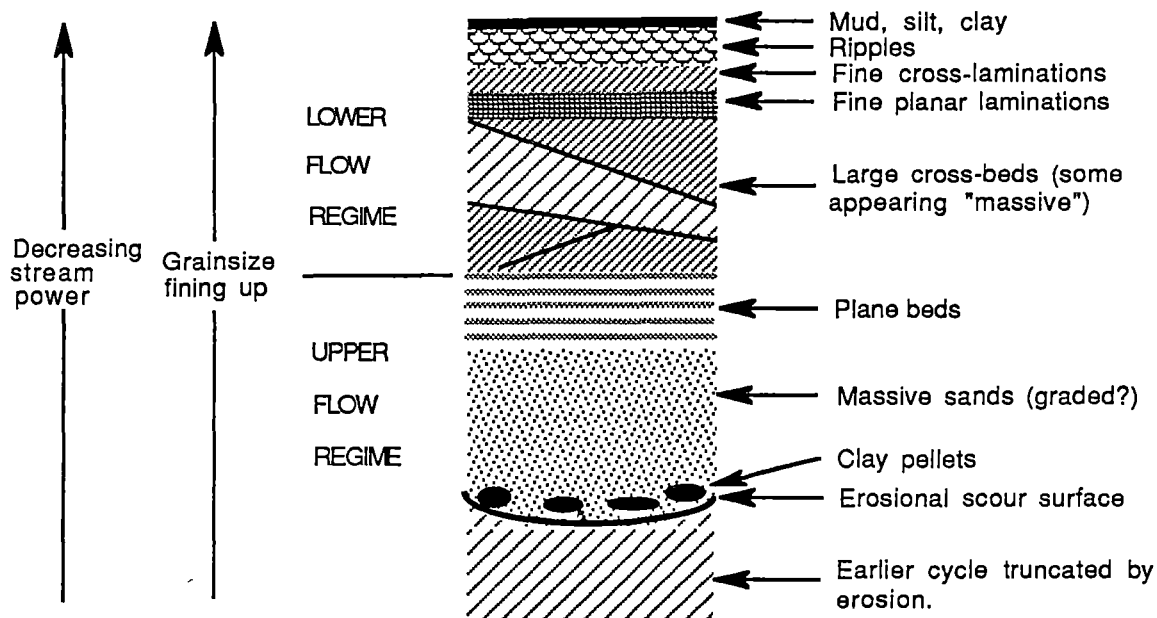


FIGURE 7.5 Ideal sequence of bedding types for meandering fluvial system sandstones.

The entire ideal sequence may not be deposited or preserved. If deposition is a result purely of progressive lateral migration of point bars, then the upper flow regime bedforms may not be produced (as illustrated in Allen 1982 p.95) and each cycle will commence with a lag deposit overlain by cross-beds (sometimes faint enough to appear "massive"), plane laminations, ripples or small cross-beds, and finally by a thin lutite layer.

In other cases a cycle might begin with a flood initiating a sudden change in flow patterns, causing rapid point bar migration and cutting of new channels. In this case the floodwaters would erode and transport a highly concentrated load of sand, silt and clay pellets from older point bars. As the flood begins to wane and river flow patterns settle into a new equilibrium, the sediment load would be rapidly dumped, forming a lag deposit (clay pellets) and a true massive bed of sand (the latter probably having some degree of graded bedding fining up).

Following this, the model predicts that plane beds (upper flow regime) would be deposited. However these are often absent, as in the Nunamara deposit (see Fig. 3.2). A possible explanation is that following a flood the rivers tended to return rapidly to a lower flow regime, by-passing the plane bed phase. Cross-beds and the remainder of the sequence would then be deposited during normal point bar accretion.

Subsequent flooding or migration of channels may erode all or part of these sequences, allowing a new cycle to be deposited. With basin subsidence, old cycles will be partially or wholly preserved and overlain by new cycles.

The model described above was developed through studies of point bar deposition in meandering fluvial systems, of which the Permian Nunamara deposit (Source 25) is considered to be an example (see Ch. 3). However, Forsyth (*in* Burrett & Martin 1989, p.320) notes that palaeocurrent vectors in the Lower Triassic Quartz Sandstone Sequence indicate deposition by low sinuosity streams, and Collinson *et al.* (1987) regard the Sequence as a braided (rather than meandering) stream system deposit, with migrating



Plate 7.2 Massive bed overlying plane-laminated sandstone at Elderslie Quarry (Source 26). Also shown are superficial pachydermal fractures on the natural weathered outcrop surface.



Plate 7.3 Cross-bedded sandstone, with distinct laminae lined with mica and graphite. Elderslie Quarry (Source 26).

channel, braid bar and sand flat environments.

Whilst Collinson *et al.* regarded large-scale fining-up lateral accretion beds as being more characteristic of meandering stream deposits in Tasmanian Middle to Upper Triassic sandstones, similar cycles are also commonly observed in Lower Triassic deposits (see below).

Coleman (1969) found that the mid-channel sandbars (braid bars) in the Brahmaputra River, a modern braided fluvial system depositing dominantly sand-size sediments, undergo rapid migration resulting in the deposition of both large and small scale crossbeds. Such migration of braid bars (and channels) could be expected to result in the formation of lateral accretion deposits in much the same way as occurs in the better-studied point bar environment, with braid bar deposits accumulating as the centres of the main river channels move away from a given point in a braid bar.

Thus, the lateral accretion model is probably broadly applicable to the braided system deposits of the Lower Triassic, as well as to meandering system deposits such as the Permian Nunamara sandstone deposit.

(Coleman also found that the braid river levees, formed largely of overlapping splay deposits laid down during floods, show a vertical sequence with fairly massive, poorly sorted silts and sands overlain by well-developed crossbeds. These in turn are overlain by plane laminations and then by ripple cross-laminated sands and silts. This sequence is very similar to the ideal lateral accretion sequence discussed above.)

Entire ideal accretion cycles were not observed in the Quartz Sandstone Sequence during this project. It is common for entire exposures to consist of only one bedding type, or alternations between two types such as cross-bedding and planar laminations, or cross- and apparent massive bedding.

No statistical analysis of bedform sequences has been attempted in this project. In several quarries apparently massive beds are interbedded with cross-bed horizons (eg, sources 12,14,17, and 21), while in several others cross-bed horizons lie directly upon apparently massive beds (eg, sources 5,6, and 16). In two of the latter (5 and 6) the cross-bed units are overlain by planar-laminated units which are thus probably formed under lower flow regime.

In the Early Triassic Quartz Sandstone Sequence (Rp) of the Oatlands area of Tasmania, Forsyth (1984) has noted that bedding cycles typically begin at the base with massive and cross-bedded medium to coarse grainsize sandstone, with common lenses of mud-pellet conglomerate. Higher in the cycle cross-bedding occurs in medium to fine-grained sandstone, and at this level the cross-beds are often overturned (deformed). Near the tops of cycles smaller scale cross-bedding, ripples, and planar-laminated beds of fine-grained sandstone occur. Siltstone occurs rarely.

Forsyth gives no figures for the thickness of cycles. Taking the sandstone sequence (Rp) as a whole, Forsyth notes that low-angle cross-bedding, planar beds and ripples are more predominant in cycles towards the top.

The typical bedding cycle described by Forsyth corresponds closely to the "ideal" lateral accretion cycle suggested above, with upper flow regime planar beds again being absent.

7.5.2 Controls on bedding thickness

Bedding thickness influences the thickness of blocks which can be extracted free of major horizontal splitting planes, which usually occur as the boundaries of major beds or cross-bed sets.

Bedding thickness is partly related to sand grainsize (Blatt *et al.* 1972,p.115), with coarser grainsizes tending to occur in thicker beds. Since a regime of gradually decreasing stream power allows coarser grains to be deposited first, followed by finer grains as stream power wanes, the typical pattern is that grainsize fines upwards through a depositional cycle (as noted in Tasmanian Triassic quartz sandstones of the Oatlands quadrangle by Forsyth 1984). This in turn implies that thicker bedding will occur in the coarser sands towards the base of each depositional cycle.

On a broader scale, grainsize can be expected to decrease upwards through a sequence of repeated depositional cycles due to slowly reducing streampower as the sedimentary basin fills and the relief of its erosional source area is reduced. Forsyth (1984,p.41) has noted such a broad pattern in the Early Triassic Quartz Sandstone Sequence of the Oatlands quadrangle: grainsize shows a general reduction from mainly coarse and medium grained in the basal 70 metres, through medium and fine grainsizes, to mainly fine grained near the top. Leaman (1976) has noted a similar pattern in the Early Triassic Quartz Sandstone Sequence of the Hobart and Brighton quadrangles.

Variation in grainsize also may occur laterally: on a regional scale in fluvial systems, the grainsize of sediments transported and laid down at greater distances from their source area tends to decrease. However, apart from pebbly sandstones of possible Early Triassic age in the Lake St. Clair region, no progressive grainsize gradient has been noted in the Quartz Sandstone Sequence across the Tasmania Basin (see Section 3.3.2).

7.5.3 Bedding Dip

Most Tasmanian Triassic (and Permian) sandstones have low-angle bedding dips, generally less than 15° (from horizontal). These dips can be attributed to minor warping during basin subsidence, intrusion of Jurassic dolerite bodies, and to tilting of large fault blocks during Jurassic and Cainozoic faulting (eg, see Leaman 1976).

The dips are normally sufficiently gentle to not be a major consideration in building sandstone exploration.

7.5.4 Keys to location of appropriately bedded building sandstones

The available information gives few indicators as to where, on a regional basis, sandstones of a given bedding type and thickness might be found.

One general indicator is the observation (Leaman 1976, Forsyth 1984 & *in* Burrett & Martin 1989) that grainsize tends to decrease towards the top of the Early Triassic Quartz Sandstone Sequence as a whole, and that the upper units have greater proportions of low-angle cross-beds, planar bedding and ripples. We can thus broadly expect to find coarser, thicker-bedded massive or cross-bed units more prevalent in the lower parts of the Early Triassic sequence.

Within individual depositional cycles, coarser and thicker-bedded units, including massive (or apparently massive) units, can be expected to be more prevalent low in each cycle.

(Note that in this context, in searching for "coarser" grained sandstones, we are really searching for medium-grained as opposed to fine-grained stone; sandstone of actual coarse grainsize category (0.5 - 1.0 mm grain diameters) normally cannot be used for building stone, for aesthetic and other reasons.)

In regard to regional grainsize variations, there is little evidence for a notable lateral gradient in average grainsize (or bedding thickness) across the Quartz Sandstone Sequence deposits of the Tasmania Basin (see Section 3.3.2). In terms of grainsize and bedding, the entire Early Triassic depositional basin, except for the coarse sandstones on the western and northwestern margins, appears to be prospective for building sandstones.

A useful field indicator of thick-bedded sandstones is that they commonly form large, bold outcrops. This is for a similar reason to widely jointed sandstones forming bold outcrops; the thicker bedding means fewer planes of weakness for weathering and erosion to attack.

Beyond the above, the most useful pointer to the occurrence of particular bedding types is the fact that the various bedding types are repeated through repeated depositional cycles. Examination of bedding in the sources studied in this project indicates that particular bedding types occur in layers varying in thickness from less than one to ten metres or more.

This means that it will commonly be possible to find several different bedding types within the same, or closely spaced, outcrops. Thus, if for instance a durable stone with perhaps planar bedding is located, it is likely that similar stone with massive or cross-bedding occurs within a short distance above or below.

Given that there is an "ideal" sequence of bedding types (Fig. 7.5), one might expect to be able to predict the location of massive (or other) bedding types on a local or outcrop scale by observation of local bedding sequences. In practice, however, such detailed prediction is rarely feasible due to the unpredictable truncations and variations of the ideal sequence which occur in the real world (see section 7.5.1).

7:6 COLOUR AND COLOUR PATTERNING

The prevalent types of colouration in Tasmanian Early Triassic and Permian quartz sandstones can be listed as follows:

- A) Uniform grey/white bulk colouration (rarely tinged faint green).
- B) Uniform brown (or yellow/orange/reddish) bulk colouration (ferruginous pigmentation).
- C) Regular brown liesegang ring (ferruginous) patterns superimposed on (A) or (B).
- D) Irregular brown (ferruginous) patches, bands, spots or nodules superimposed on (A) or (B).
- E) "Bleached" white patches superimposed on brown ferruginous patterning.
- F) Miscellaneous minor patternings superimposed on (A) or (B), including black manganese dioxide staining, circular patches of subtle darkening, green ?reduction spots, and others.

The colour of Tasmanian sandstones depends primarily on the presence or absence of ferruginous minerals (iron oxides or hydroxides), as discussed in section (2.4.2).

There is little evidence that any of these colouration types have a significant influence on stone durability. Although significant quantities of dense ferruginous cement may slightly increase stone strength in some cases, the relative proportions of clay and silica forming intergranular bonds are the over-riding determinant of stone strength.

The main criterion for choosing colouration types in building stones is aesthetic, so that in principle any of the above types can be used in appropriate circumstances. In practice, sandstone of uniform bulk colouration, or with subdued liesegang rings, tends to be preferred for large-scale exterior cladding, while stone with strong liesegang rings or other ferruginous staining patterns (C or D) tends to be preferred for smaller scale ornamental features.

7.6.1 Iron minerals in sandstone

Since iron minerals in sandstone are the principle components determining colouration, it is necessary to briefly mention their geochemistry in preparation for the following discussion of sandstone colouration processes.

Iron occurs in minerals in two forms, ferrous (Fe^{2+}) and ferric (Fe^{3+}). Ferrous iron minerals tend to be stable under reducing conditions (Krauskopf 1967,p.253), but change to ferric iron under oxidising conditions.

The ferric minerals are the main contributors to brown sandstone colourations. Ferric iron oxides or hydroxides are soluble under acid conditions, but become insoluble or very sparingly soluble (and so precipitate) when pore waters become alkaline (Winkler 1973,p.134).

Of the ferric minerals, iron hydroxide (goethite) has commonly been identified during this project in X-Ray Diffraction analyses of clay fraction mounts prepared from a wide range of

Tasmanian Early Triassic quartz arenites. Iron oxide (haematite) was not positively identified in any sandstone during this project.

Common iron-bearing minerals which may occur in sandstone are listed below:

Ferrous (Fe ²⁺) (sulphides and carbonate)	Pyrite	FeS ₂	yellow (black if fine)
	Marcasite	FeS ₂	yellow
	Siderite	FeCO ₃	yellow to brown
Ferric (Fe ³⁺) (oxides and hydroxides)	Haematite	Fe ₂ O ₃	black to red
	Goethite	FeO.OH	brown
	(Limonite = amorphous goethite)		yellow)
Ferrous + Ferric Magnetite		Fe ₃ O ₄	black (stable in reducing environments)
	Muscovite (Fe very minor)		colourless
	Biotite		black, brown
	Hornblende		black, green
	Augite		brown, black, green
	Kaolinite (Fe rare)		white
	Illite (Fe minor)		white
	Smectite (Fe minor)		white
	Nontronite (Fe-rich smectite variety)		green
	Chlorite		green, sometimes white or yellow
	Vermiculite		colourless, yellow, brown, green

7.6.2 Origin of colouration; data used and it's limitations

Little research has yet been done on the origins and causes of the various colouration types and patterns found in Tasmanian sandstones. Systematic work on the problem has not been carried out in the present work, although a number of possible colouration processes have come to light.

Since colouration is of great importance in building stones, it seems worth recording these possible processes here. It must be noted that due to the incomplete nature of the data used, the following ideas remain little more than speculations. It is to be hoped that work on the problem of colouration will be undertaken in a more systematic basis.

The following discussions refer specifically to Tasmanian Early Triassic quartz sandstones only, although similar principles probably hold true for Permian fluvial quartz sandstones.

Middle - Upper Triassic lithic sandstones of pale grey-greenish fresh bulk colouration often form a strong brown weathering bulk colouration within only two or three metres of outcrop surfaces. This behaviour, which is thought to be related to a higher content of chlorite (see later discussion), does not seem to be common in the quartz sandstones. Although the latter may form a brown or reddish weathering "rind" within a few millimetres of natural outcrop surfaces, they generally maintain either a brown or grey/white bulk colour from within a few millimetres of the surface down to significant depths.

The data used in the following speculations comprises:

- A) Previous literature (as noted).
- B) Data on sandstone quarry sources (Appendix One, and relevant information abstracted in Appendix Nine).
- C) Data obtained during sandstone exploration work carried out for Rizzolo Stone & Concrete Pty Ltd in 1987-88, used with permission and listed in Appendix Eight.

There are several important limitations and biases in these data sources:

- A) The data in Appendices One and Nine are mainly limited to sandstones whose colourations have previously been considered "attractive". Obviously the colouration of "unattractive" sandstone is just as important in understanding colouration processes.
- B) The data in Appendix Eight is biased towards sandstones of brown bulk colouration and free of strong ferruginous patterning, since that is the type which was being sought.
- C) A differentiation was not made between chlorite and vermiculite in Appendix Eight, since the original purpose of the clay analyses was simply to check for the presence of smectite.
- D) The data is not distributed evenly geographically, and it has not been possible to finely differentiate stratigraphic horizons within the Early Triassic Quartz Sandstone Sequence, due to limitations in existing mapping. This makes speculations on geographical or stratigraphical influences tentative at best.

7.6.3 Origin of Bulk Colourations

(A) Grey/white bulk colouration

On available evidence, it appears likely that the original depositional colour of Early Triassic sandstones in Tasmania was the grey-white bulk colouration (see Plates 4.1, 4.4, 7.6).

Hale (in Spry & Banks 1962,p.219) noted that Early Triassic sandstones in bore-cores are grey, although weathering may persist for over 100 metres in depth and changes the colour to yellowish or reddish-brown. Farmer (1985,p.54) noted that Early Triassic sandstones in the Kingborough quadrangle (south of Hobart) are generally grey or cream in colour, but weather to brown, while Camp & Banks (1978) found that sandstones in the Knocklofty quarry (Source No. 8) are grey or very pale green when fresh, developing oxidation colours only when weathered.

The palaeomagnetic pole lay only 10° to the SE of Tasmania during Triassic times (McElhinny & Embleton 1974), although there is no evidence of either very cold or very warm conditions (Camp & Banks 1978). According to Camp & Banks, Early Triassic deposition may have taken place in a cool temperate or sub-polar arid or seasonally arid region, perhaps a little like the Patagonian desert today.

Dapples (*in* Larsen & Chilingar, 1979, Ch.2), noted that many streams (ie, fluvial environments) have slightly acid waters (pH 5 - 7), which indirectly tend to keep iron in

a reduced ferrous form (and any ferric oxides remain soluble (Winkler 1973,p.134)), so that red/brown oxidised minerals only precipitate after deposition in an environment of higher pH, such as the sea (approx. pH 8). Thus, with the Early Triassic sands being deposited in a fluvial environment, probably under cool arid conditions which would also serve to inhibit oxidation (Krauskopf 1967,p.116), it is likely that they would have been buried without significant precipitation of brown iron oxides.

According to Dapples, the final bulk colour of sandstone is established in the environment of early burial. This early stage of diagenesis, termed the "redoxomorphic" stage by Dapples, occurs during initial compaction, ejection of fluids, and prior to lithification. This stage is dominated by oxidation and reduction reactions. Once the reactions have oxidised or reduced whatever iron is available, there is much less tendency to reverse the equilibrium during the later history of the rock, so that the initial bulk colour tends to be preserved.

Many of the Triassic sandstone quarries and outcrops studied in this project have indeed preserved their (probably original) grey/white colouration throughout burial, diagenesis, uplift and weathering (see Fig. 7.8), so that even in outcrop it is commonly found that only the outer 10 mm or so (directly exposed to the atmosphere) has oxidised to a red or brown colour.

(B) Brown bulk colouration

However, there seem to be two main situations in which the original grey/white has altered to a brown colouration. One is the production of ferruginous staining patterns associated with Jurassic dolerites and late-stage exposure and weathering (to be discussed below).

The other, which is the subject of this section, is the production of a uniform brown bulk colouration, due to ferruginous minerals disseminated evenly (rather than in a patterned fashion) throughout the sandstone matrix in the form of tiny grains, or as staining of the clays (see Plate 7.26). Such bulk colouration may not necessarily be related to any known outside sources of iron such as dolerite, and apparently extends well below the surface in some areas. Sandstones exposed near Oatlands, Melton Mowbray and Elderslie are good examples of this brown bulk colouration (see Plate 7.4).

Evidence such as the observation of Hale (in Spry & Banks 1962,p.219) that brown colouration may occur to a depth of over 100 metres, but eventually passes down into grey sandstones in bore cores, strongly suggests that the production of brown bulk colouration in Tasmanian Triassic sandstones is a phenomenon associated with uplift and/or downwards movement of the zone of oxygenated groundwater circulation, resulting in commencement of weathering by oxidation (see Fig. 7.8).

It is known that oxidation zones can extend to hundreds of metres below ground surface in conditions where porosity, fracturing, and other factors allow the deep circulation of oxygenated meteoric waters. In sufficiently oxidising conditions of this nature, iron-bearing porewaters may precipitate iron oxides or hydroxides, producing the uniform brown bulk colouration.

A problem that needs to be answered is the question of why brown bulk colouration may be produced to significant depths by such oxidation in some areas, while the original grey/white colouration will persist right to the surface in other areas.

This problem cannot be fully solved simply by proposing that variations in water table, fracture systems, porosities, permeabilities, and so forth allow oxidation to proceed to

greater depths in some areas than in others. If the depth of the oxidation zone was the only factor involved, we could not expect to find any grey/white sandstones outcropping at the surface at all, since even the shallowest oxidation zones in the least permeable present day quartz sandstone outcrops would allow oxidation and colour change to at least a few metres depth.

It could be proposed that brown bulk colouration forms in sandstones which have a nearby source of iron-rich rocks (eg, dolerite or basalt) from which iron-rich groundwater may flow into the sandstone. However, many uniform brown sandstones (eg, many parts of the widespread outcrops of uniformly brown sandstone near Elderslie) are 1.5km or more from the nearest known dolerite or basalt. This suggests that transport of iron from outside sources such as mafic igneous rocks is not essential for brown bulk colour formation in sandstones (although such processes may in some cases be contributing factors).

It seems more likely that the cause of bulk colouration variation lies primarily in the availability of iron to be oxidised within the sandstones themselves, rather than in the availability of outside iron sources.

A number of iron-bearing minerals are known to occur in Early Triassic Tasmanian sandstones. Muscovite and biotite may occur, with varying amounts of iron. Morad (1984, p.1162) notes the presence of small amounts of iron oxide pigment in Swedish Proterozoic greywackes, which appears to have formed as a result of diagenetic alteration of biotite. Although present in Tasmanian sandstones (Eggert 1983), biotite is generally a very minor component and so would only make a minor contribution to colouration.

Hale (Spry & Banks 1962, p.219) recorded magnetite, tourmaline, garnet, ilmenite and siderite in the sandstones, but these have rarely been reported in anything other than trace amounts in the Quartz Sandstone Sequence, and seem unlikely to have a major influence on the production of ferruginous colouration.

Of the minerals occurring commonly in the quartz sandstones, clays are the most likely iron sources. Kaolinite is usually free of iron, while illite and smectite generally have only minor amounts of iron.

On the other hand, vermiculite occurs commonly (and chlorite less commonly) in the Quartz Sandstone Sequence, and may contain considerable amounts of iron (Deer, Howie & Zussman 1966). It can therefore be suggested that vermiculite and chlorite may be a primary source of iron in Early Triassic sandstones which have not received any input of iron from outside sources such as dolerite intrusions.

With uplift and onset of oxidising conditions through exposure to oxygenated groundwaters, the iron in vermiculite and chlorite may be leached out and iron oxides or hydroxides may then be precipitated under alkaline subsurface conditions (approx. pH 7 - 9: Fairbridge, *in* Larsen & Chilingar, 1967, p.32), staining the remaining clay masses and giving the stone a uniform brown bulk colour (see Fig. 7.8).

These processes might cause partial or complete breakdown of the iron-depleted vermiculite and chlorite clays to form other clays.

Microscopic examination of the sandstones seems in accordance with this idea, since ferruginous minerals very commonly occur as stainings of clay masses, and in some cases a physical transition can be observed over a few microns or tens of microns, from lightly stained clays to masses apparently composed entirely of ferruginous cement.

Basic data collected during this project seems to support the above hypothesis:

Using the data from Appendix One (summarised in App. Nine) and Appendix Eight for quarries and other outcrops in which both bulk colouration and clay types present were determined, (and ignoring data on strongly ferruginous-patterned sandstones whose bulk colouration may have been affected by the patterning processes as described later) the present bulk colouration is compared to clay types present in Table 7.1 below:

BULK COLOURATION		
Clay Types present	Brown	Grey/White
Illite \pm Kaolinite \pm Smectite only	16	13
I \pm K \pm S + vermiculite or chlorite (undifferentiated)	12	1 (trace)
I \pm K \pm S + vermiculite	3	-
I \pm K \pm S + chlorite	1	1 (trace, green tinge)
TOTAL	32	15

TOTAL DATA POINTS: 47

TABLE 7.1 Clay matrix types and Bulk Colouration for Early Triassic Tasmanian sandstones. Note that in many cases vermiculite and chlorite were not differentiated, since this requires an extra stage in the XRD analysis, and the original purposes of the analyses was merely to test for the presence of smectite.

Data: Appendices 8 & 9, omitting data on strongly ferruginous-patterned stones.

Of the 15 sandstone sources having a grey/white bulk colouration, only 2 (13%) contain either vermiculite or chlorite, and then only in trace amounts.

Of the 32 sources having brown bulk colouration, 16 (50%) contain either vermiculite or chlorite, and commonly in significant amounts.

This data gives a strong indication that the presence of vermiculite or chlorite is associated with the occurrence of a brown bulk colouration. It can be further speculated that some brown sandstones presently appearing to lack vermiculite or chlorite may have originally contained these minerals but have had them completely altered to other clay minerals during leaching and oxidation processes which produced the ferruginous colouration minerals. More detailed work (such as careful XRD or SEM to look for relict chlorite or vermiculite) could test this possibility.

For instance, the writer suspects (but cannot presently prove) that the brown colour of the Linden Quarry sandstone is due to vermiculite alteration. The quarry is peripheral to the

main area of known vermiculite occurrence (Elderslie - Oatlands: see Section (C) following), but no vermiculite has been identified in the stone. It is possible that the stone contained just enough vermiculite to produce a brown colour as a result of complete vermiculite breakdown.

It may additionally be pertinent to investigate the possibility that other minerals such as smectite, which may have a small iron content, may contribute to brown bulk colouration if present in sufficient quantities. This could be the case with the brown high-smectite Port Arthur and Domain sandstones, for instance (see Plate 7.9).

Of the quarries and outcrops listed in Appendices (8) and (9), omitting those with strong ferruginous patterning, 16 sites have sandstone of brown bulk colour which is lacking in either vermiculite or chlorite (Table 7.1). Of these, 9 sites (56%) have in excess of 10% smectite (or mixed layer illite/smectite) in their clay matrices.

Vermiculite vs Chlorite as a source of brown bulk colour in Triassic sandstones

Although vermiculite and chlorite were not differentiated in most of the XRD analyses used in Table (7.1), where this was done the clay in question in brown sandstones was found to be vermiculite in three out of four cases. Furthermore, vermiculite has been positively identified in the quarries at Elderslie, Melton Mowbray and Oatlands (Appendix One). It therefore seems highly likely that the undifferentiated vermiculite/chlorite in numerous nearby and stratigraphically equivalent outcrops is in fact vermiculite (See Appendix 8 and Fig. 7.10).

While the suspected predominance of vermiculite over chlorite in brown Early Triassic sandstones needs to be demonstrated more rigorously (as proposed in Chapter Nine), a number of resulting observations and speculations are worth discussing here:

Chlorite appears to be relatively common in Tasmanian Middle to Late Triassic sandstones. Threader & Bacon (1983) report chlorite in Late Triassic sandstones, and Forsyth (*in* Burrett & Martin 1989,p.330) notes that chloritisation of the Late Triassic sandstones is common.

During the present project, Lithic sandstones of Middle Triassic age (Unit 3 of Forsyth 1987) were examined in a road-cutting near Kempton (grid ref. EN166913). The fresh sandstones in this outcrop have a pale greenish-grey colour. However, within two or three metres of the natural outcrop surface, a brown bulk colouration is developed (see Plate 7.5).

Samples of both the fresh grey-green sandstone, and the brown near-surface stone, were subjected to XRD analysis. (samples S/Ts/66/1/1 & 2, see Appendix Two, numbered according to a system developed by the writer during work for the Tasmanian Development Authority; see Sharples 1990) Smectite, illite and kaolinite are present in both samples. However, whereas the fresh grey-green stone contains an abundance of iron-rich chlorite (Ripidolite, basal spacing 7.07 Å), chlorite is absent in the brown near-surface sandstone.

These results strongly suggest that the brown near-surface bulk colour in this outcrop has resulted from the iron-rich chlorite breaking down (through leaching by meteoric waters, and oxidation) within only two or three metres of the natural outcrop surface, with resultant precipitation of iron hydroxides and/or oxides.



Plate 7.4 Uniformly brown vermiculite-rich Early Triassic quartz sandstone. The brown colour extends to an unknown depth. Midlands Highway road cutting at Melton Mowbray (adjacent to Melton Mowbray quarry, Source 34).



Plate 7.5 Greenish-grey chloritic Middle Triassic lithic sandstone, showing brown colouration close to the natural outcrop surface. Kempton (EN166913).

Further examples of similar near-surface browning of grey-green Middle-Late Triassic deposits have been observed in numerous other road cuttings along the Midlands and Lyell Highways (between Oatlands and Dysart, and between Gretna and Plenty, respectively). It is also noteworthy that one of the two specimens in Table (7.1) in which chlorite was positively identified in Early Triassic sandstone is from the grey-green coloured Kangaroo Point Green Sandstone (Source 4).

It is suspected that two distinct types of brown bulk colouration are developed in Tasmanian Triassic Sandstones:

- 1) Vermiculite is common in Early Triassic rocks of the Quartz Sandstone Sequence, and where present experiences leaching and precipitation of oxidised iron minerals to significant depths. This process produces deposits of brown bulk-coloured sandstones extending to depths of tens (perhaps over a hundred) of metres below the ground surface. Chlorite, on the other hand, is a minor component in the Quartz Sandstone Sequence.
- 2) Chlorite is common in Middle to Late Triassic rocks, and is related to a pale grey/green fresh bulk colour. These sandstones retain their fresh colour to within only a few metres of the natural outcrop surface, where the chlorite is leached and its iron oxidised to yield a brown ferruginous bulk colouration.

One corollary of this hypothesis is that vermiculite appears to be more susceptible to leaching of its iron and precipitation of oxidised ferruginous minerals than does chlorite, since the process appears to affect vermiculites at significant depths, whereas cases are observed in which chlorite is only so affected in sandstones within a few metres of the atmosphere.

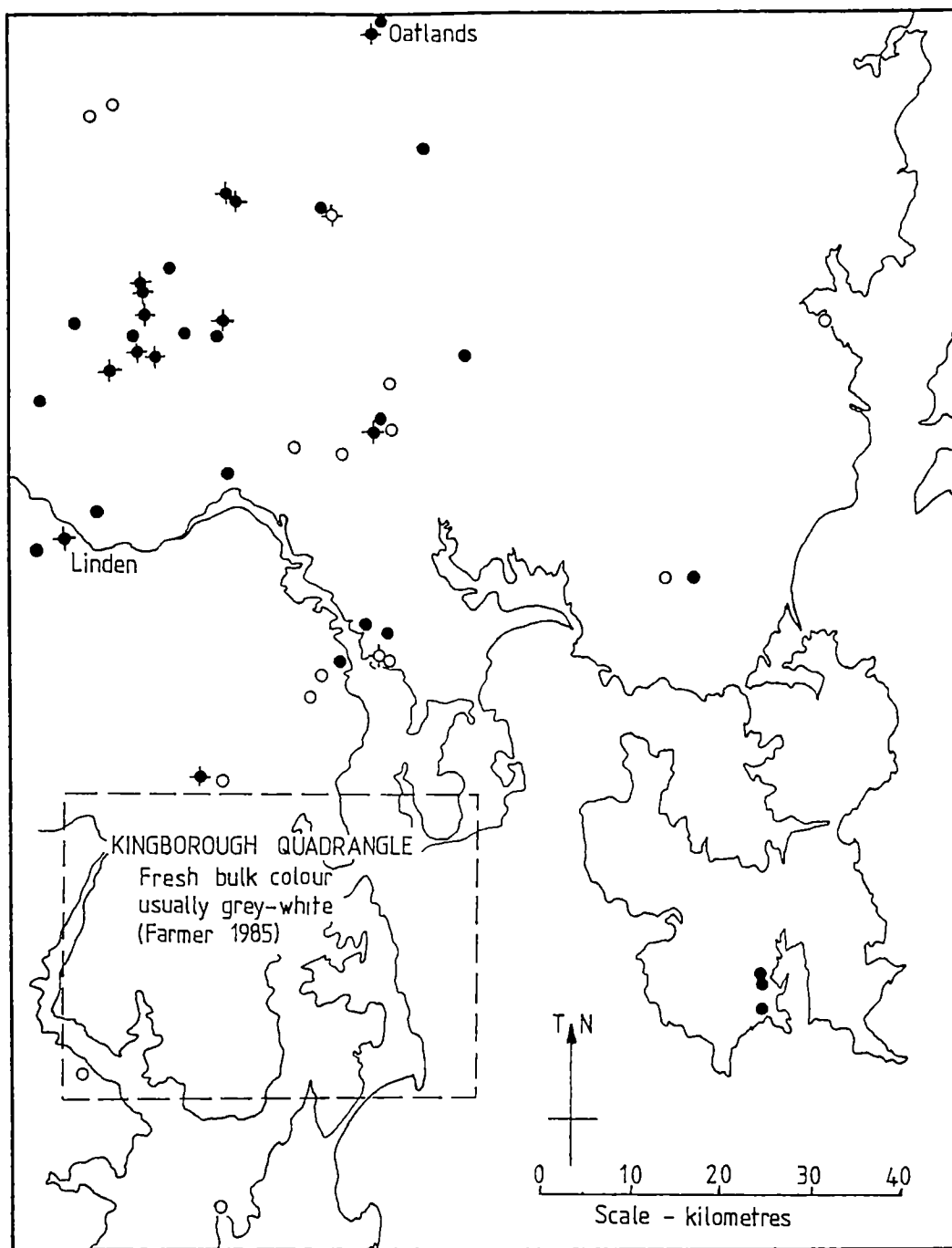
(C) Geographic and stratigraphic patterns in bulk colouration

The available data is suggestive of geographical and stratigraphic patterns in the distribution of Early Triassic sandstone bulk colourations, and of the (probably related) distribution of vermiculite (as well as smectite and chlorite?) in those sandstones:

Figure (7.6) maps the location of all the south-east Tasmanian sources used in Table (7.1), plus several extra data points for which bulk colouration was recorded but clay types not determined. Additional bulk colouration information from Farmer (1985) is indicated, that being the only published work on sandstones in the SE Tasmania region which records regional patterns of bulk colouration.

The data is very limited in that there is little stratigraphic control, and the geographical distribution of data points is very uneven.

However, with these limitations in mind, there does appear to be an indication of a broad band of sandstones having brown bulk colouration, and commonly containing vermiculite (and/or chlorite?), extending from Linden in the SW to Oatlands in the NE (see Fig. 7.6). Many of these occurrences are from outcrops mapped as basal Early Triassic Quartz Sandstone Sequence (Rls of Leaman 1977) or undifferentiated Quartz Sandstone Sequence. Further uniform brown Quartz Sandstone Sequence deposits containing vermiculite or chlorite (probably vermiculite) have been noted in the Blessington - Englishtown region, near Launceston (Sharples 1989c, included in Appendix Eight and Table 7.1; see also Fig. 7.10).



KEY · ○ Grey - white bulk colour
 ● Brown bulk colour
 ⊕ Vermiculite or chlorite present

DATA : Appendices 8 & 9, omitting sites with strong iron oxide patterning (bulk colour may be affected), but including a few with clay types not determined.

FIGURE 7.6 Geographical distribution of bulk colourations and clay types in Early Triassic sandstones, SE Tasmania.

A broad area of sandstones having grey/white bulk colouration, and mostly lacking in vermiculite or chlorite, appears to stretch from the Hobart region south-eastwards into the Kingborough quadrangle, and are mostly mapped as undifferentiated Early Triassic Quartz Sandstone Sequence.

This distribution of bulk colourations and clay types suggests three possibilities:

- 1) There may be a geographic control on the distribution of vermiculite (and chlorite?), and thus of bulk colourations, due to variations in Early Triassic palaeogeography and depositional environments. Since the presence of vermiculite is possibly related to vulcanism (see Section 7.8.3), the location of the volcanic centres may be relevant.
- 2) There may be a stratigraphic control, with vermiculite (and chlorite?) content being greater in the more basal sandstones. If vulcanism is implicated in the occurrence of the vermiculite, this would suggest more vulcanism lower in the Early Triassic.
- 3) A combination of the above.

The significance of these patterns of vermiculite distribution is discussed further in Section (7.8.3). Further work with more data is necessary to properly investigate these possibilities.

7.6.4 Origin of Ferruginous Staining Patterns

As used herein, the term "ferruginous stain patterns" refers to discrete bands or patches of red, orange, brown or yellow iron oxides or hydroxides superimposed upon the bulk colouration of sandstones, rather than to the brown ferruginous bulk colourations described above.

Whereas the source of iron for brown bulk colourations appears to be iron-rich minerals within the sandstone itself, the evidence presented below suggests that ferruginous stain patterns result (at least in part) from an input of iron from outside sources.

Ferruginous stain patterns may include the common Liesegang rings - regularly repeated rings or bands arranged concentrically (see Plates 4.9, 4.10, 4.11, 7.7, 7.8)- as well as regular spherical or ellipsoid spots, patches and nodules (see Plate 4.5), or irregular bands and patches. In addition, an ferruginous reddening of the surface 10mm or so of sandstone outcrops is a common weathering phenomenon.

Microscopically, ferruginous stain patterning generally involves precipitation of significant quantities of dense ferruginous masses, partly filling the intergranular spaces, in addition to the simple staining of clay masses which is more prevalent in sandstones of brown bulk colouration but lacking stain patterning.

Of these patterns, Liesegang rings are predominant in Tasmanian Early Triassic sandstones, and most of the following discussion concentrates on them (Sections A, B & C below).

(A) The origin of Liesegang Ring patterns.

It is generally considered that liesegang rings form as a weathering phenomenon in near surface sandstones, through rhythmic precipitation of ferruginous minerals in zones of fluctuating water table levels which cause periodic desiccation of iron-rich pore-waters.

However, two distinct hypotheses can be proposed to explain liesegang ring formation:

- (1) At least some liesegang ring formation has certainly resulted from near-surface weathering processes. This is most clearly seen to be the case where rings are found parallel to naturally weathered faces (other than planar faces formed by pre-existing planar joint surfaces along which earlier ring formation processes could have acted, as per (2) below).
- (2) There is some evidence which can be interpreted as suggesting that the strong liesegang ring patterns which commonly pervade large volumes of sandstone could result not from weathering processes, but from processes related to (and contemporaneous with) intrusion of Jurassic dolerite bodies.

It is the purpose of the following discussion to consider and evaluate both these hypotheses.

Figure (7.7) presents data on sandstone quarries and outcrops studied in this project (Appendices Eight and Nine), graphically comparing the degree (or "strength" as defined in Appendix Eight) of ferruginous patterning present with the distance of the outcrop from the nearest known dolerite contacts. Note that while liesegang rings predominate, the data includes other types of ferruginous patterning.

The following inferences can be drawn from Figure (7.7):

- (1) There is a clear tendency for strong to moderate ferruginous stain patterns to occur predominantly in sandstones within 500 metres (most commonly within 300 metres) of a known dolerite contact. This strongly suggests that the large quantities of iron required to form strong ferruginous patterns are derived from the iron rich dolerite. The general lack of strong ferruginous patterning away from dolerite bodies implies that other sources, such as iron minerals originally present in the sandstone, do not provide sufficient iron to form strong patterns (although they may be sufficient to form less intense ferruginous stain patterns, as well as the overall brown ferruginous bulk colourations).

A well exposed example illustrating the relationship occurs in a long road-cutting near Longley, southern Tasmania. At site 47/1 (App.8, EN156415), well exposed sandstone approximately 250 metres from a mapped intrusive dolerite contact has strong ferruginous colouring. The same sandstone horizons can be traced continuously away from the dolerite contact until at site 47/2 (EN155417), 400 metres from the contact, ferruginous staining has faded in intensity to the point of being virtually absent.

Of the four cases in Fig. (7.7) in which strong or moderate staining occurs at greater than 500 metres from a known dolerite contact, at least one site (1/1) is thought to have originally been much closer to an overlying (now eroded) dolerite sill (Leaman 1976, Fig.11). The possibility of similar close contacts with hidden or now-eroded dolerite bodies can be suspected in other cases.

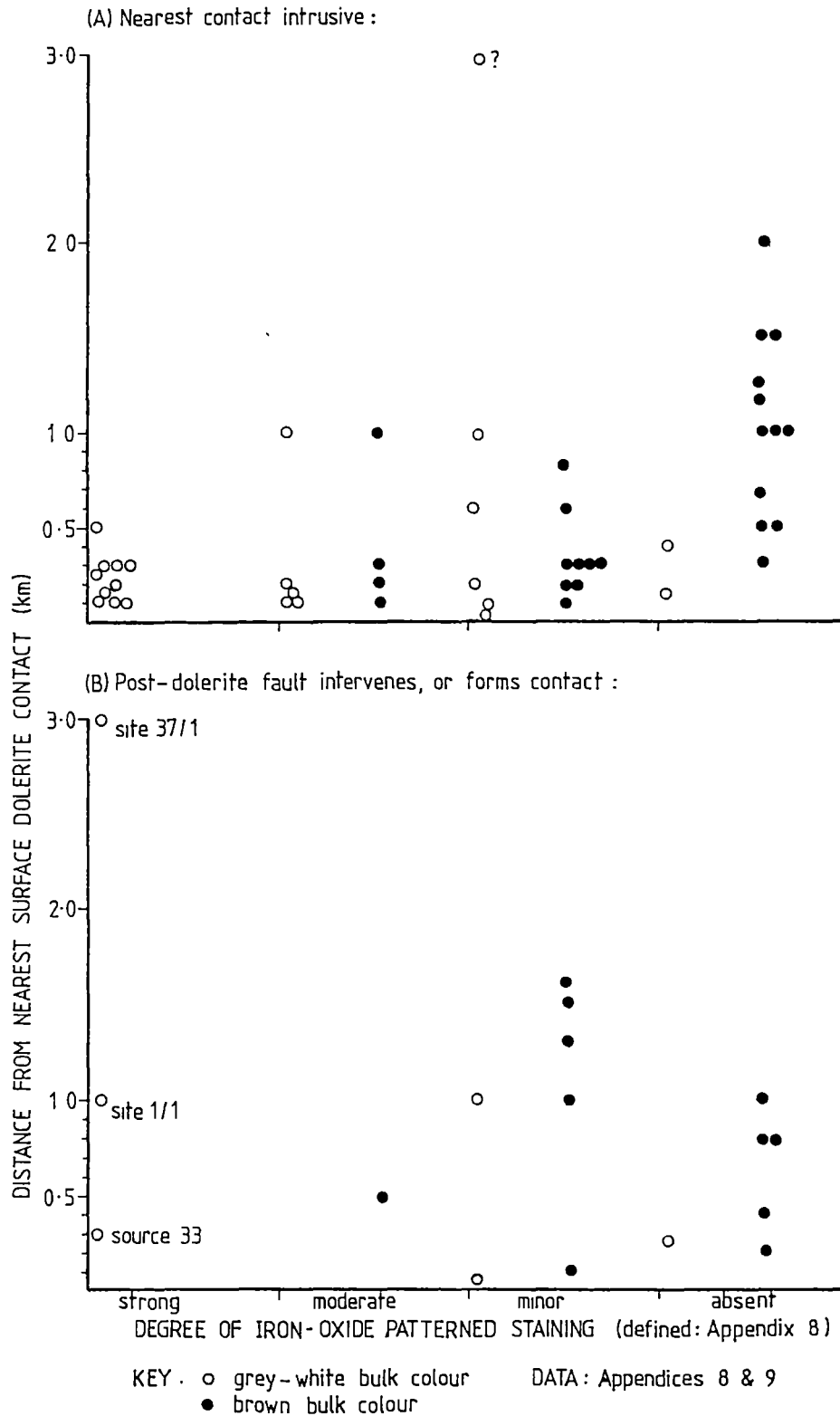


FIGURE 7.7 Comparison of degree of ferruginous stain patterning (as defined in Appendix 8) with distance from nearest known contacts (usually surface) with dolerite bodies; Early Triassic sandstones, Tasmania Basin.

- (2) Both brown and grey/white bulk colourations may occur at any distance from dolerite contacts, supporting the contention made in the previous discussion that bulk colouration is generally the result of original compositions and diagenetic processes unrelated to the proximity of dolerite.
- (3) Strong to moderate ferruginous patterning occurs predominantly where the nearby dolerite contacts are intrusive, rather than being faulted contacts which brought the sandstone and dolerite into juxtaposition after intrusion. This can be interpreted in one of two ways:

(A)

It may mean that strong staining is precipitated contemporaneously with dolerite intrusion, rather than being a result of late-stage groundwater transport of iron from the dolerite into the sandstone during near-surface weathering processes. Thus, by the time later faulting brings dolerite into juxtaposition with previously unstained sandstone, the staining process is no longer active, and no further staining takes place.

Since some of the faults separating unstained sandstone from adjacent dolerite are themselves of Jurassic age, and probably moved during or soon after dolerite intrusion, a very brief period of primary pattern formation contemporary with intrusion is suggested (otherwise these sandstones would be strongly stained as a result of being brought into proximity to the recently-intruded dolerite).

(B)

Alternatively, if strong ferruginous patterning is only a recent weathering phenomenon, it suggests that iron-bearing groundwaters flowing out of the dolerite tend to be conducted away from the sandstone along intervening faults. It is only when no fault intervenes that the iron-rich waters can pass directly across the intrusive contact and permeate the sandstone.

Section (C) below discusses the implications of these alternative interpretations and discusses evidence and possible tests to determine their validity.

There are only three cases in the present data of strong staining occurring in sandstone whose nearest presently known dolerite contact is a fault:

Site 1/1: Original nearest dolerite contact was actually closer and intrusive (See (1) above).

Source 33: The fault existed prior to dolerite contact, and became an intrusive pathway. Thus the "faulted" contact is in reality intrusive.

Site 37/1: Situation unknown.

- (4) A significant number of cases exist of sandstones within 500 metres of intrusive dolerite contacts which show little or no ferruginous patterning. These cases are in need of explanation. Possible causes include:
 - Variations in bedding or porosity affecting the degree to which iron-rich fluids can pass through the sandstone.

- Iron-rich waters emanating from the dolerite may move through the sandstone in sharply defined pathways or "lobes", producing discrete patches of liesegang ring patterning immediately adjacent to large patches of unstained stone. This effect is clearly seen in the Buckland Quarry (Source 28; see Plate 7.6), and may also be responsible for the presence of unpatterned stone in the Pontville White Stone Quarry (Source 22), which is immediately adjacent to strongly patterned stone in the Pontville Brown Stone Quarry (Source 21).

- A "bleaching" or reducing process subsequent to liesegang ring formation may remove staining. Small-scale bleaching of this nature is probably responsible for small bleached patches truncating liesegang ring patterns in the Bothwell Rifle Range Quarry (Source 17).



Plate 7.6 Uniform grey-white sandstone, showing abrupt boundary with "lobe" of strong liesegang ring staining at right hand side. Note red surface rind on LHS (see Section 7.6.4 D). Buckland Quarry (Source 28).

(5) The strongly patterned sandstones have a grey/white (rather than brown) bulk colouration, upon which the brown ferruginous stain patterns are superimposed. However, stone with only moderate or minor stain patterning may have a brown bulk colour. This observation suggests several possible causes:

- A sampling bias: The strongly patterned stones with grey/white bulk colour were chosen for quarrying because their light bulk colouration makes the patterning stand out better?

- The nature of the patterning process may be such as to leach out any iron originally present in the sandstone bulk and redeposit it only in the rings and other staining patches, leaving the surrounding sandstone mass iron-free and therefore incapable of developing a brown bulk colour inbetween the

ferruginous rings or patches. In cases of less intense patterning, this process would not proceed to completion, so that some iron would remain as a brown bulk colour.

- (6) Basalts, being of similar iron-rich basic chemistry to dolerites, also produce ferruginous patterning. An example is exposed in cuttings on the Southern Expressway between Kingston and Browns River, where liesegang rings have formed in Triassic sandstone adjacent to a Tertiary basalt intrusion (R. Donaldson, *pers. comm.*). However insufficient data on sandstones adjacent to basalts has been collected in this project for the processes involved to be investigated.

It has been established that evidence exists implying a genetic relationship between the presence of dolerite contacting sandstone bodies along intrusive rather than faulted contacts, and the formation of strong ferruginous stain patterns in those sandstones.

Two mechanisms have been suggested to fit the evidence: either ferruginous staining occurs contemporaneously with dolerite intrusion into the sandstone mass, as a result of hot iron-rich fluids moving out of the intruding magma, or else it is a late stage near-surface phenomenon resulting from iron-rich groundwaters passing from the weathering dolerite into adjacent sandstones in situations where the waters are not diverted away along faults.

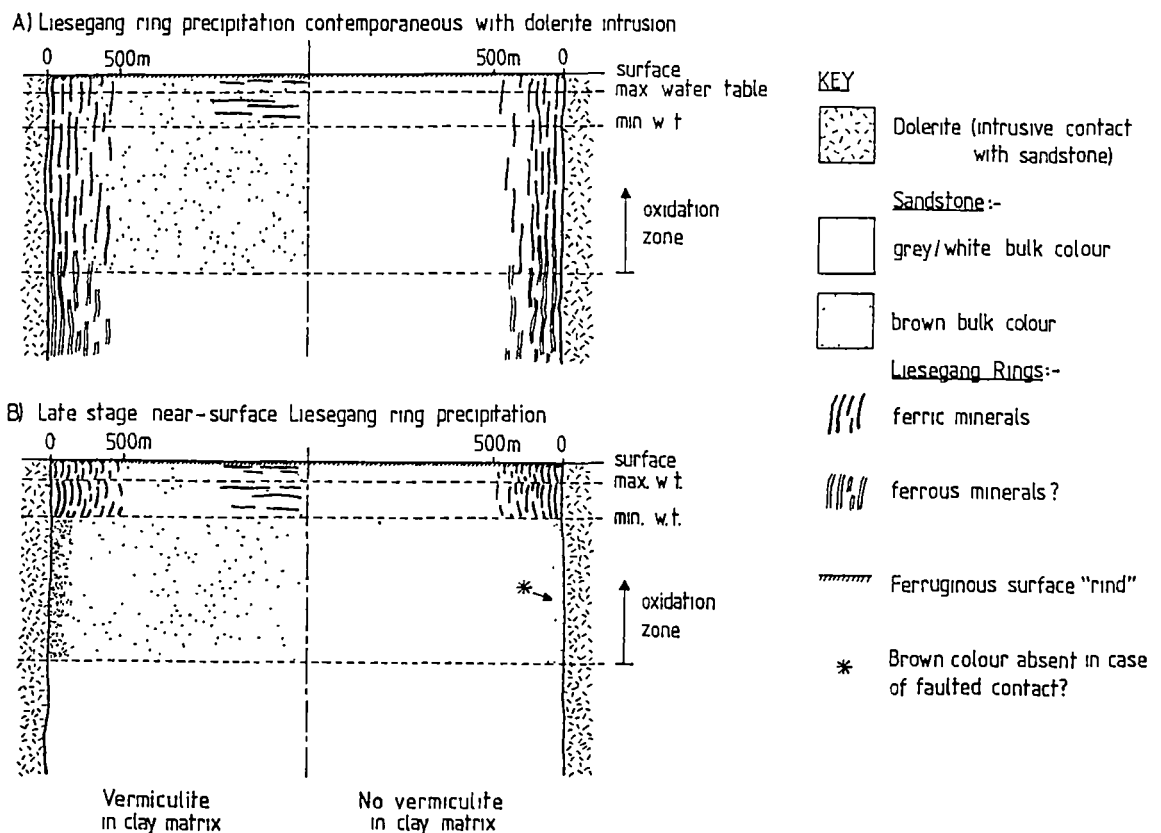


FIGURE 7.8 Patterns of Liesegang ring distribution predicted by theories of (A) pattern formation contemporaneous with dolerite intrusion, and (B) late stage near-surface pattern formation. The figure also indicates bulk colour distributions predicted by the discussion in Section (7.6.3).

Each of these theories has different implications, which can be tested by field and drilling observations. Evidence and tests to determine the validity of each theory are discussed in Section (C) below, while Fig. (7.8) gives a graphic illustration of the patterns of Liesegang ring distribution predicted by each theory.

However, a further approach to discriminating between the two ferruginous staining mechanisms proposed is to examine what is known of the process of Liesegang ring formation in order to see whether it is compatible with either or both of the proposed mechanisms. (Liesegang rings are considered in detail because they are the predominant form of ferruginous patterning encountered.)

(B) Mechanisms of Liesegang Ring formation

The precipitation of Liesegang rings in sandstones is still not a fully understood process.

Liesegang rings are repeating precipitation patterns, generally consisting of concentric rings of precipitate separated by relatively clear spaces. They were first observed in 1896 by R.E. Liesegang, who demonstrated rhythmic banding by diffusion of silver nitrate in the colloid gelatin. Liesegang recognised them as diffusion phenomena resulting from periodic alternation between solution mobility (diffusion) and supersaturation (nucleation and precipitation).

Liesegang rings are commonly formed in nature by diffusion of an electrolyte through a colloid which may be in the form of a gel (Krauskopf 1967, p.156). For instance, Krauskopf (p.166) suggests that the rhythmic banding of agates is due to such diffusion in a silica gel.

However, the action of colloids or the presence of a gel is not essential (Stern 1954), and Gore (1938) has demonstrated that iron hydroxide (goethite) may form Liesegang rings by diffusion through a non-gelatinous medium. This process is likely to be responsible for formation of Liesegang rings in porous sandstones.

Stern (1954) proposed that supersaturation processes can account for the gross features of Liesegang rings. The process begins with a solution (eg, of iron rich waters) diffusing through a material (eg, porous sandstone). Precipitation (of iron minerals) occurs when the solution becomes highly super-saturated, so that the dissolved material is no longer metastable in solution. Precipitation occurs in a ring a short distance behind the diffusion front. Material still in solution diffuses towards the precipitation nuclei, leaving a depleted space through which further dissolved material must travel until saturation again builds up to the supersaturation limit at which precipitation occurs to form the next ring. Thus, regularly spaced rings of precipitate are formed with clear spaces between them.

It is possible that Liesegang rings in sandstones can result from diffusion through the stone of ferric hydroxides in the form of either true solutions, or colloidal suspensions (sols).

Diffusion through sandstone may occur by either ionic diffusion (colloidal ferric hydroxide particles carry an electric charge - Krauskopf 1967, p.157), or by the capillary action which can be expected in such a porous medium as sandstone (Winkler, 1973, p.112).

According to Liesegang (1945, *in* Winkler 1973, p.112), if capillary action prevails, the distance between the rings grows smaller outwards, and finally several rings may join to form one very thick band. This phenomenon is commonly observed in Tasmanian sandstones, suggesting that capillary diffusion is an important process in these stones.

Carl & Amstutz (1958), and Fairbridge (*in* Larsen & Chilingar, 1967,p.56) note that liesegang rings may form during weathering processes. The banding probably forms with oxidation and a change in pH of the pore waters from acid towards more alkaline, which greatly reduces the solubility of ferric oxides and hydroxides so that they precipitate out (Winkler 1973,p.112).

Fairbridge (*Ibid.*) suggested that in such cases of liesegang rings formed by weathering, desiccation of the pore-waters is necessary to provide the supersaturation required for ring formation. Each ring would then represent the maximum extent of a diffusion front prior to the desiccation which caused supersaturation to occur.

We can surmise that the ferric oxides and hydroxides present in pore waters precipitate as a uniform bulk colouration at constantly saturated depths below that affected by desiccation (as proposed in Section 7.6.3 B), whereas they precipitate as liesegang rings in the near-surface zone affected by periodic desiccation (ie, the zone of fluctuating groundwater saturation between the maximum and minimum water table levels).

From this it may be concluded that liesegang rings formed as a weathering phenomenon in Tasmanian sandstones which do not have an outside source of iron (such as a nearby dolerite body) are likely to be poorly developed, since:

- a) Sandstones which still have a grey/white bulk colouration when exposed in the near-surface desiccation zone probably have little iron available within them, and,
- b) Sandstones which have a brown bulk colouration in the near-surface desiccation zone are likely to have already had most of their available iron precipitated as (insoluble) ferric oxides and hydroxides during earlier (deeper) stages of uplift and oxidation.

A small degree of relatively faint liesegang ring development is likely to occur through late-stage breakdown of minerals such as Fe-bearing smectite and vermiculite during surface weathering (see Section 7.11.1).

The precipitation of strong Liesegang ring patterns appears to require the proximity of an abundant outside supply of iron carried by groundwater from sources such as nearby basic igneous intrusions.

(C) Evidence and tests to determine mechanisms of Liesegang ring formation

It is evident from the above discussion that current theory supports the proposal that Liesegang ring formation is a late stage near-surface weathering-related phenomenon resulting from the dissolution in groundwater of iron from iron-rich dolerite bodies, movement of that groundwater into adjacent sandstones, and precipitation of the iron there as rings of iron oxide or hydroxide minerals.

The evidence which suggests the possibility that liesegang rings may instead (or in addition) be formed contemporaneously with sub-surface dolerite intrusion is the observation that Liesegang ring are absent or less-well formed in situations where the contact between the dolerite and the sandstone is a fault which has moved subsequent to dolerite intrusion. The validity of this alternative theory depends upon whether near-surface iron-rich groundwaters can easily cross the fault in question and permeate the sandstone on the other side, or whether the fault would instead tend to conduct the iron-rich groundwaters away

from the sandstone.

If groundwater can be expected to easily cross a fault rather than being conducted away, then if Liesegang rings are indeed formed by late stage near-surface groundwater transport of iron into the sandstone, it would be expected that strong liesegang rings would form in sandstones adjacent dolerite bodies regardless of whether the contact is intrusive or faulted. In fact, they do not; they normally are only formed if the contact is intrusive. This would imply that liesegang rings formed earlier, during the dolerite intrusion phase, and that the later fault movement brought unstained sandstone, which at the time of intrusion was situated beyond the range of the dolerite-related staining process, into close juxtaposition to the dolerite after the staining process became inactive.

On the other hand, if faults do conduct iron rich waters away from the sandstone, then the theory that liesegang ring formation is a late stage near-surface process is not disproved since the intervening fault would inhibit liesegang ring formation even in sandstones very close to dolerite.

There are a number of considerations and tests which will contribute to determination of which of the two theories of liesegang ring formation is valid (or whether both could apply in particular cases):

(1) Behaviour of groundwater in and across faults

As stated above the validity of the evidence for a liesegang ring formation process contemporaneous with dolerite intrusion hinges upon whether iron-rich groundwaters can cross faults from the dolerite on one side into the sandstone on the other during late-stage near-surface weathering, or whether most of the groundwater emerging from the dolerite would in fact be conducted away from the sandstone along the fault.

In fact, particular faults are known to behave in either of these two ways. Typically, a sharp, clean fault break may divert groundwater along it and act as a conduit or groundwater "flow barrier". On the other hand, wider fault zones filled with clay and shattered rock can in many cases allow significant diffusion across the fault into rocks on the other side (R. Donaldson, *pers. comm.* 1990).

Thus, the evidence regarding the effect of faulting on liesegang ring formation is ambiguous. In order to clear up this ambiguity, it would be necessary to examine good exposures of each fault in question, and/or to obtain evidence on groundwater flow across the fault from measurements in adjacent boreholes.

Nevertheless, one studied sandstone deposit, the Tea Tree Quarry (Source 13), does provide some suggestive evidence pertinent to the relationship between faulting and liesegang ring formation.

The Tea Tree Quarry contains sandstone of uniform grey/white bulk colouration which is free of Liesegang rings despite a dolerite contact only 250 metres southeast of the main face. The nature of the dolerite/sandstone contact is unusual: The contact was a Mesozoic fault which existed prior to dolerite intrusion, and along which dolerite intruded so that it became, in effect, an intrusive contact. However, further movement subsequently occurred along the faulted/intrusive contact (Leaman *et al.* 1975). The amount of post-intrusion movement along the fault is unclear, but appears to have been relatively small. The sandstones were probably at a similar distance from the intruding dolerite as they are at present (see Fig. 3 in Leaman 1977).

Since it appears that the quarried stone was close to the intrusive dolerite contact at the time of intrusion, liesegang rings would be expected to have formed in the sandstone if the ring formation process was indeed active at the time of intrusion. That they did not is evidence against the theory, and supports the theory of ring formation in near-surface oxidising environments.

This being so, the continued post-intrusion movement along the contact has further significance in that it meant that by the time the sandstone was exposed to near surface oxidising conditions the dolerite/sandstone contact was again a true faulted contact. Since liesegang rings were not formed at this stage either, it suggests that the faulted contact was indeed diverting iron-rich groundwaters away from the sandstone.

Thus, the Tea Tree sandstone quarry provides some evidence that:

- (A) Liesegang rings do not form contemporaneously with dolerite intrusion. and,
- (B) Faults do tend to conduct groundwater emerging from dolerite away from adjacent sandstone bodies.

While the Tea Tree Quarry appears to provide evidence damning the theory that liesegang rings form contemporaneously with dolerite intrusion, two critical pieces of data are not clear:

- a) The exact distance of the sandstone (in the existing quarry) from the dolerite contact at the time of intrusion.
- b) The nature of the intervening fault (clean and sharp, or a clayey shatter zone?).

Further corroborating evidence therefore needs to be sought in addition to this single instance.

(2) Are the physical and chemical conditions of dolerite magma intrusion conducive to Liesegang ring formation?

The theory that liesegang ring formation occurs contemporaneously with dolerite intrusion implies that during intrusion hot iron-bearing magmatic waters pass out from the dolerite magma into the sandstone country rock. Precipitation of ferruginous rings results not from periodic dessication causing supersaturation at the diffusion front (as in the near-surface groundwater theory), but rather to a buildup of saturation in rhythmic pulses behind an advancing (single event?) front of hot magmatic waters diffusing through the sandstone (as suggested by Stern (1954), *see* (B) above).

It is probable that magmatic waters emerging from from the dolerite magma at depth would have been reducing. Therefore, the ferruginous minerals precipitated in Liesegang rings formed contemporaneously with dolerite intrusion would probably have been ferrous minerals such as siderite or pyrite. These minerals would have oxidised to the brown ferric minerals characteristic of outcropping liesegang rings only upon later exposure to near-surface oxidising conditions

Leaman (1975), Clarke & Baillie (1984), and Farmer (1985) have noted that contact metamorphism associated with the Tasmanian Jurassic dolerites is confined to only a few metres of country rock surrounding intrusive contacts. From this Leaman (*Ibid.*) and Farmer (*Ibid.*) concluded that the dolerite was a "dry" magma low in aqueous phases.

This conclusion tends to militate against the idea that magmatic fluids from the dolerite could penetrate some hundreds of metres into surrounding sandstones to produce contemporaneous liesegang rings. On the other hand, liesegang ring formation involves much less alteration of the country rock than do contact metamorphic processes such as production of contact hornfels through silicification. It could be suggested that such iron-bearing magmatic fluids as emerge from a "dry" magma would still be sufficient for liesegang ring formation, but this problem clearly needs clarification.

An easier approach to clarifying the origin of liesegang rings is to look at other lines of evidence. If other tests such as those proposed below can demonstrate an origin for liesegang rings contemporaneously with intrusion, then it will be clear that the phenomenon has occurred, and the problem will then be one of discovering how a dry magma can produce such effects. On the other hand, a clear demonstration that liesegang rings only form under near-surface weathering conditions will obviate the need for closer scrutiny of dolerite intrusion processes from this particular point of view.

(3) Evidence from jointing patterns

In Tasmanian sandstones it is normal for Liesegang rings to be arranged concentrically about joint fractures (see Plate 7.7). It seems clear that the iron-rich waters (whether magmatic or late-stage groundwaters) have primarily moved into the sandstone deposit along the joints, and permeated the joint blocks from there. Conversely, during dessication of pore-waters in near-surface deposits, water would move concentrically out from the centres of joint blocks towards the bounding joints, so that precipitation of the iron resulting from this dessication would form rings sub-parallel to the joints.

As noted in section (7.4.1 A), most jointing in Tasmanian Triassic sandstones can be related to two tectonic events, a Mesozoic event active both before and after the dolerite intrusion, and a later Tertiary event.

If most liesegang ring formation took place contemporaneously with dolerite intrusion in the Mesozoic, then liesegang rings would be concentric about Mesozoic joints formed during or before the dolerite intrusion, but not about later Tertiary joints (indeed, in this case liesegang rings could be expected to be cut across by Tertiary joints without any other effect on the pattern of liesegang ring distribution). On the other hand, if liesegang ring formation is a late stage near-surface process, the rings would have formed concentrically about both Mesozoic and Tertiary joints.

Thus, if it is possible to determine the age of joints which have liesegang rings concentric about them (by a method such as comparing the average strike of the joints in question with the strikes expected for local Mesozoic and Tertiary joints, or by some other means), then we would have a powerful test of the two theories of liesegang ring formation.

A slightly different, but related, line of evidence is provided by the Buckland Quarry (Source 28). The main face of this quarry (as at March 1990) has extremely widely spaced joints, with up to 30 metres horizontally between minor joints. The face is dominated by a set of long undulating sub-horizontal liesegang rings which are clearly sub-parallel to the similarly undulating natural upper surface of the outcrop, and which appear to be becoming less intense at depths below four metres, near the base of the face (see Plate 7.8).

This clearly suggests late-stage liesegang ring formation parallel to the outcrop surface, with ring formation primarily occurring in the layers of stone closest to the surface. As a corollary it suggests that, where there are no closely spaced joints about which liesegang rings can become concentrically arranged, the rings must precipitate parallel to the ground



Plate 7.7 Liesegang Rings controlled by joint planes. Molesworth Quarry (Source 29).



Plate 7.8 Liesegang rings sub-parallel to natural outcrop surface in very widely jointed sandstone. Buckland Quarry (Source 28).

surface, which is the only available discontinuity towards which iron-rich waters can be conducted, and from which they can be evaporated, during periods of dessication (ie, dry weather).

(4) Evidence from drilling

The theory that liesegang rings are formed at depth during dolerite intrusion implies that the rings will be found adjacent to dolerite intrusions at significant depths below the present-day zone of surface oxidation, albeit the rings may be expressed as less-noticeable rings of ferrous minerals rather than as the red-brown ferric minerals which form the rings in the oxidation zone. On the other hand, if liesegang rings only occur in the near-surface oxidising zone of fluctuating water-table levels, then they will not be found below that zone in any form (see Fig. 7.8)

Therefore a conceptually simple method of testing the two theories is to drill sandstone near an intrusive dolerite contact to a depth below the level of water table fluctuation (and preferably to below the oxidation zone), and note which of the two possible situations holds true.

Ideally, such a drill-hole would be collared in sandstone having strong liesegang ring patterning at the surface, within 200 metres or so of a near-vertical intrusive dolerite contact. In such a situation, the variations in liesegang ring abundance and the nature of their expression could be followed to depth at an approximately constant distance from the dolerite contact.

While it is unlikely to be considered worthwhile to drill such a hole purely for the purpose of testing these theories, it may be that core from an existing hole in such a situation is already available for examination. Alternatively, in future drilling conducted for stratigraphic or other reasons, it may be feasible to site such a hole in a position where information pertinent to liesegang rings can be obtained in addition to whatever other information is sought.

Conclusion

While the evidence currently to hand does not permit a definitive decision to be made as to which of the two possible theories best accounts for the presence of strong liesegang ring patterns in sandstones adjacent to dolerite intrusions, the evidence does appear to lean towards the theory that these patterns are produced by near surface groundwater processes.

In particular, the dry nature of the dolerite magma and the situation at the Tea Tree and Buckland quarries appear to support this conclusion.

Further work utilising the last two tests outlined above (jointing and drilling evidence) will be able to settle the question conclusively.

(D) Other ferruginous stain patterns - patches, bands, nodules and surface "rinds".

Aside from Liesegang rings, the most common ferruginous stain patterns found in Tasmanian Early Triassic quartz sandstones are light diffuse patches, scattered ferruginous spots or nodules, and the common surface "rinds" of ferruginous minerals which form thin (10mm or so thick) layers on outcrop surfaces.

Diffuse patches and banding

Light brown or reddish patches of ferruginous staining are common in the Quartz Sandstone Sequence, and may occur as irregular patches up to several hundred millimetres in diameter, or as bands following particular beds. While these patterns are commonly found in association with Liesegang rings, they have not been studied in any detail, other than to suggest that ferruginous staining along particular beds may be related to increased porosity in those beds allowing easier diffusion of iron-rich groundwaters along them.

Ferruginous spots or nodules

Brown to brownish-red iron oxide or hydroxides commonly occur as faint oval or circular (spherical) spots or nodules scattered randomly through the stone and varying in size from diameters of about 1mm to over 100mm. They may occur as a light staining of the stone or may be dense nodules consisting almost entirely of ferruginous minerals. Whilst they most commonly form only a minor, randomly scattered component of the stone, in cases such as the Bothwell Flagging Quarry (Source 32) they may be an abundant component dominating the appearance of the stone.

Two typical examples are:

Bothwell Flagging Quarry (Source 32):

Reddish-brown spots dominate the stone's appearance, predominantly occurring as small spots about 1mm diameter, but also present as oval patches elongated along bedding and up to 100mm + diameter. The spots are a staining of the sandstone fabric, and Liesegang rings are not present. The nearest known dolerite body outcrops approximately 200 metres away and has an intrusive contact.

Cobbs Hill Quarry (Source 23):

Dark ferruginous nodules 10 - 15mm diameter are scattered randomly in a typical concentration of about 40 nodules per square metre of stone faces (see Plate 4.5). The nodules are dense, consisting almost entirely of iron oxide or hydroxide, and Liesegang rings are not present in the stone. The nearest known dolerite body crops out over 1 kilometre away.

While no special study of ferruginous spots and nodules were made in this study, a few observations can be made:

From the lack of associated Liesegang rings and the distance to dolerite bodies in some examples, we can infer that the processes of spot and nodule formation are not necessarily closely related to those of Liesegang ring formation.

Rather, the morphology and distribution of the spots and nodules suggests that they form from randomly distributed nuclei in the stone. The most likely explanation would appear to be that spots and nodules form by oxidation of scattered grains or masses of iron minerals present within the stone (for instance, Fairbridge, *in* Larsen & Chilingar (1967), considers that nodules of limonite and haematite form by oxidation of pyrite or other iron

minerals). Presumably individual scattered grains or masses of such minerals are involved, and such minerals are not necessarily a common component of sandstone, since spots and nodules are not abundant in a significant proportion of sandstone deposits.

This is as opposed to a uniform distribution of very fine ferruginous mineral masses, derived from a pervasive vermiculite or chlorite matrix (see Section 7.6.3 B), which would give rise instead to an overall brown bulk colour.

Such scattered iron-bearing minerals grains could include pyrite, marcasite, siderite, magnetite, biotite, hornblende, or augite, some of which are known to occur in trace amounts in Early Triassic Tasmanian sandstones (Section 2.2.6), but only in a proportion of deposits, and generally only as scattered grains or nodules (eg, siderite nodules are known, which are often altered to limonite - S.F. Forsyth, *pers. comm.* 1990).

The formation of brown spots and nodules would probably commence at the same time as the formation of brown bulk colouration (ie, at the earliest stage of uplift at which oxidising groundwaters become prevalent) and might continue in the near surface weathering zone as long as some iron is still available for further oxidation.

In a case such as the Bothwell flagging stone, which is near enough to an intrusive dolerite contact that the formation of liesegang rings would normally be expected, it is possible that as iron-rich groundwaters from the dolerite permeated the sandstone the iron from the dolerite failed to form liesegang rings because it instead precipitated on the scattered ferruginous nuclei already present in the stone.

Ferruginous surface "rinds" on sandstone outcrops

It is common to find a reddish-stained layer of sandstone occurring in the outer 10mm or so of exposed natural sandstone outcrops (eg, see Plate 7.6, LHS). These "rinds" may form on sandstones which are quite free of liesegang rings, although in some cases a series of very weak parallel liesegang rings may extend 100 millimetres or so into the stone from the (most intense) outer surface rind "ring".

Where sandstone has been covered by a thin soil layer, the surface rind which forms at the sandstone/soil interface can be a very dense ferruginous deposit (still generally less than 10mm thick), as opposed to the simple ferruginous staining of sandstone which occurs on exposed outcrops.

These rinds clearly form through the complete evaporation of groundwater at the surface of the stone where it is exposed to the atmosphere. All iron present in the waters must precipitate at this surface, so that even if only very small amounts of iron are present in the pore-waters, precipitation at the outcrop surface will eventually lead to a strongly-coloured ferruginous ring building up (see also Section 7.11.1).

The cause of the denser ferruginous rinds at sandstone/soil interfaces is unclear.

7.6.5 "Bleaching" and "reduction spots" in ferruginous sandstone colouration

At the Bothwell Rifle Range Quarry (Source 17), liesegang ring patterns are in places interrupted and truncated by randomly distributed "bleached" white patches up to several centimetres in diameter. The bleached patches are the same grey-white colour as the bulk colour of the stone, on which the liesegang rings are super-imposed. The bleaching has clearly occurred subsequent to the formation of the liesegang rings.

At the Elderslie Quarry (Source 26), patches of pale greenish-brown sandstone up to 100 mm or more in diameter occur randomly scattered. The greenish patches are oval in shape, elongated parallel to bedding direction, and only occur in the massive bed in the quarry (none have been noted in cross-bedded horizons immediately adjacent).

It is suspected that both these phenomena result from a reduction process; however the precise mechanisms are unclear.

7.6.6 Keys to location of appropriately coloured building sandstones

Three primary colouration types are found in Tasmanian Early Triassic sandstones of the Quartz Sandstone Sequence. Keys to the location of each are as follows:

Uniform grey-white bulk colouration

These sandstones typically have a low-iron mineralogy, with a clay matrix consisting of illite \pm kaolinite \pm smectite, but free of significant vermiculite. A pale greenish-grey variety may occur in instances where chlorite is present which has not altered to yield a brown near-surface ferruginous colouration (eg, Kangaroo Point Green Sandstone Quarry).

Uniform grey-white sandstone is generally found at distances of over 500 metres from intrusive dolerite contacts, although they may be found closer in certain circumstances (eg, at the Buckland and Pontville White Sandstone quarries). They may occur at any distance from faulted dolerite contacts (eg, Tea-Tree Quarry).

Otherwise, no geographical or stratigraphic pattern is evident in the distribution of uniform grey-white sandstone, except insofar as they are minor or absent in regions dominated by uniform brown sandstone.

Uniform brown bulk colouration

These sandstones are dominated (in the Quartz Sandstone Sequence) by vermiculite-rich varieties, in which iron derived from the vermiculite is considered to have produced the finely dispersed intergranular ferruginous minerals which are responsible for the brown colour. The presence of chlorite may produce a similar effect immediately below outcrop surfaces, although this appears to be less common in the Quartz Sandstone Sequence. Some high-smectite sandstones may also have a brown bulk colour due to iron derived from smectite alteration.

Uniform unpatterned brown sandstone is generally found at distances of over 500 metres from intrusive dolerite contacts. They may occur at any distance from faulted dolerite contacts (eg, Elderslie Quarry).

There is evidence of a geographical (and stratigraphic?) pattern in the distribution of brown vermiculite-rich sandstones. Although the geographical pattern is not yet well defined, due to paucity of data, there is clear evidence of a distinct "belt" of these sandstones extending from the Elderslie area north through Melton Mowbray to the Oatlands region. Further similar sandstones occur in the Blessington region, near Launceston.

Brown Liesegang ring patterned sandstones

Strong brown liesegang ring patterns are characteristic of sandstones within 500 metres (most commonly 300 metres) of intrusive dolerite contacts, but will not necessarily be found in sandstones close to faulted dolerite contacts. Strong liesegang rings are rarely found at greater distances from dolerite contacts, and when they are it can often be surmised that a hidden or eroded dolerite contact is implicated.

7.7 TEXTURE AND TEXTURAL "DEFECTS"

This section deals only with those macroscopic aspects of texture which are relevant to the aesthetic quality of sandstone; textural properties (including intergranular texture) which control strength and other technical characteristics are dealt with in later sections.

The ideal building sandstone will have a fine- to medium-grainsize, be moderately- to well-sorted, and contain little or no defects such as quartz pebbles, clay pellets, clay or mud bands, concretions or nodules, porous patches, or other macroscopic defects.

7.7.1 Controls on textural characteristics

Grainsize and sorting

Grainsize and sorting are controlled by the environment of deposition. Regional variations in grainsize within the Quartz Sandstone Sequence of the Tasmania basin are dealt with in the discussion on bedding (Section 7.5), and also in Chapter Three.

As noted in those sections, there is little evidence for notable lateral gradients in average grainsize across the Quartz Sandstone Sequence of the Tasmania Basin, except for the occurrence of coarse sandstones close to the western and northwestern margins of the basin.

On the other hand there is a notable decrease in average grainsize going up through the Quartz Sandstone Sequence as a whole, and also going up through individual depositional cycles. Sandstones of suitable medium to coarse grainsize are more prevalent in the lower parts of individual cycles, and within the lower parts of the Sequence generally (fine-grained to mud-size grains becoming more prevalent higher up).

No information is available on regional or stratigraphic sorting variations within the Tasmania Basin. However most Quartz Sandstone Sequence specimens examined during this project were of moderately- to well-sorted texture, and it is likely that, as with grainsize, little consistent regional variation occurs across the basin, other than within the coarse, poorly sorted horizons near the basins western margins.

A program of investigation of textural variations across the Tasmania Basin, as proposed in Chapter Nine, would be necessary to determine whether any regional or major stratigraphic patterns are evident; until this is done it is reasonable to assume that, in a regional sense nearly all of the basin is equally prospective for fine- to medium-grained and moderately - to well-sorted sandstones, although the stratigraphically lower parts of depositional cycles, and of the Sequence as a whole, are most prospective.

Quartz Pebbles

Transport and deposition of quartz pebbles in the predominantly sand- to mud-grade deposits of the Quartz Sandstone Sequence is indicative of periods of higher than average stream power, and can be expected to be most common in regions closer to the source areas.

Quartz pebbles, generally of less than 10mm diameter, are common in possible Quartz Sandstone Sequence beds on the northwestern margins of the Tasmania Basin (towards the Lake St. Clair area, see Fig. 3.3), and also on Bruny Island (see Section 3.3.2 ; pebbly horizons on Bruny Island may indicate derivation of sediments from a source area within the relatively close Tyennan Block directly to the west).

Elsewhere, they are common only in the basal few metres of the Sequence (Forsyth 1987). At stratigraphically higher levels quartz pebbles are comparatively rare, occurring concentrated in minor thin beds and in some instances as a sparsely scattered component of

otherwise moderately well sorted sandstone beds. Forsyth (1987) notes that the occurrence of quartz pebbles above the base of the Sequence is most common at the base of major depositional cycles (greatest stream power), and as thin beds in lutite rich intervals (crevasse splay?).

Clay pellets and mudbands

As noted in Section (3.3.2), as a broad generalisation lutite beds (clayey and muddy horizons) become more abundant towards the top of the Quartz Sandstone Sequence. The lutite beds probably represent cut-off channel, lacustrine and overbank deposits. Within individual depositional cycles, lutites were deposited at the top of each cycle, in its last, low energy phase.

In a regional sense, lutite deposition and preservation would be expected to be more prevalent in the distal (downstream) parts of the basin. However, no data exists to indicate that such a trend is significant in the preserved parts of the Tasmania basin (see Section 3.3.2).

Discrete bands and lenses of clay and mudstone occur in some deposits within the lower sandstone-dominated part of the Quartz Sandstone Sequence (eg, at Elderslie and Tea Tree Quarries). These probably represent instances where overbank deposits at the top of individual cycles were incompletely reworked by subsequent depositional cycles. It is not possible to predict the occurrence of such lenses and beds, except insofar as they are likely to become more common the higher one goes in the Quartz Sandstone Sequence.

Small clay pellets are relatively common throughout the Quartz Sandstone Sequence, and occur both as thin pellet-rich intervals, and sparsely scattered throughout thicker layers of sandstone. Clay pellets are formed as a result of the reworking of overbank deposits from previous depositional cycles, and so are most commonly deposited at the base of individual depositional cycles. This mode of occurrence is notable in instances such as the thick massive bed at Linden Quarry, where clay pellets are concentrated in the lower two metres or so of the new cycle represented by the massive bed.

Clay pellets will occur randomly throughout the Quartz Sandstone Sequence and are not especially predictable except insofar as they are most prevalent at the base of individual cycles.

Concretions and nodules

Ferruginous (limonite) nodules or concretions are relatively common in the Quartz Sandstone Sequence, and have apparently formed by oxidation of pre-existing concretions (eg, siderite) and mineral grains (see Section 7.6.4 D). Ferruginous concretions are common in some deposits (eg, Cobbs Hill Quarry, see Plate 4.5), but completely absent in others.

It is possible that the distribution of such nodules and concretions is controlled by the original deposition of particular mineral grains in discrete regions or horizons within the Quartz Sandstone Sequence, which in turn would be related to differences in provenance and palaeoenvironment within the Tasmania Basin. However, current data does not indicate any regional or stratigraphic patterns in the occurrence of such nodules and concretions.

Porous patches

Circular (or rather, spherical) porous patches of sandstone 10 - 30mm diameter are common in sandstones from the Pontville and Domain Quarries (see Plate 7.9). These patches are undesirable since they tend to weather more easily, and may take a slightly

darker patina upon exposure, than the surrounding stone.

The origin of these patches is uncertain; they may be either a depositional or diagenetic phenomenon. In the absence of knowledge about their origin, it is not possible to predict their occurrence.

7.7.2 Keys to location of well-textured sandstone

Apart from the prevalence of coarse, poorly sorted sandstones rich in quartz pebbles close to source areas, current knowledge indicates that, in a regional sense, the whole of the Tasmania Basin is more or less equally prospective for fine- to medium-grained, moderately- to well-sorted sandstones in the Quartz Sandstone Sequence.

Stratigraphically, there is a broad pattern of decreasing grainsize and increasing lutite content going upwards through the Sequence, and also going upwards through individual depositional cycles. Quartz pebbles and clay pellets are most common at the base of individual depositional cycles. Preserved lutite bands and lenses are likely to be more common higher in the Sequence.

Sandstones of fine- to medium-grainsize and moderately- to well-sorted texture, free of quartz pebbles, clay pellets and muddy or clayey bands, are most prevalent in the lower parts of the Quartz Sandstone Sequence, close to (but not right at) the base of individual depositional cycles.

The occurrence of ferruginous and other nodules or concretions, and of porous patches, cannot be predicted on the basis of current knowledge.



Plate 7.9

Dark porous patches in Domain Quarry (Source 7) sandstone in the Old Supreme Court, corner of Murray and Macquarie Streets, Hobart (1864).

7.8 MINERALOGY

For the greatest possible durability, building sandstones should have the highest possible content of strong, chemically and physically stable minerals (ie, quartz), and the lowest possible content of weak or unstable minerals (feldspars, micas, clays, graphite, etc). In addition, sandstones of particular desirable colourations depend upon the presence of minerals controlling colouration (see Section 7.6), including ferruginous minerals and commonly vermiculite (in the case of brown sandstones).

The mineralogy of sandstone is controlled by provenance (source rocks), depositional environment (winnowing out or dissolution of certain detrital minerals, chemical precipitation of others), diagenesis and weathering processes (authigenic mineral growth or dissolution).

Collinson *et al.* (1987) have shown that detrital components of Triassic sandstones in Tasmania (and originally contiguous sandstones in Antarctica) are derived from a mixture of sedimentary, crystalline (granitic and metamorphic), and volcanic terranes. The provenance of the Tasmanian Early Triassic sandstones was predominantly a cratonic and unroofed orogenic terrane in western Tasmania and/or further away in Antarctica (*Ibid.*), with only a minor volcanic component (partly indicated by the clay mineralogy: see Section 7.8.3 below).

Collinson *et al.* suggest the volcanic source terrane was most likely an active calc-alkaline complex along the Pacific margin of Gondwanaland (in the opposite direction from the Tasmania Basin to the cratonic sources). Volcanic sources may have contributed materials both by fluvial transport from minor (older?) sources in the direction of the craton, and (as suggested by the present work; see below) by atmospheric transport of volcanic dust from active volcanic sources along the Pacific margin.

In Middle to Late Triassic times, after deposition of the Quartz Sandstone Sequence, the active volcanic terranes became the dominant source area for the Tasmanian sandstones (Collinson *et al.* 1987, Fig. 3). As the volcanic source terrane became progressively more important in Antarctica and Tasmania during the Triassic, the result was that by the Middle Triassic the flood of volcanic sediments from the Pacific margin shifted the axis of the Antarctic-Tasmanian Basin towards the Antarctic craton (*Ibid.*). In Tasmania, the result of this was that whereas in the Early Triassic rivers flowed from the cratonic regions to the west and northwest, in the Middle to Late Triassic the rivers flowed predominantly from the volcanic terrane to the east, southeast and northeast (Forsyth, *in* Burrett & Martin 1989, p.323-333).

The following discussions deal with the Early Triassic Quartz Sandstone Sequence.

7.8.1 Quartz

Quartz is the volumetrically dominant component of nearly all sandstones in the Early Triassic Quartz Sandstone Sequence, as well as in the Permian Nunamara Quarry sandstone. Quartz occurs in the form of detrital grains, and as authigenic overgrowths on detrital grains. The presence of well-formed crystal faces on authigenic overgrowths is commonly indicated by a glittering effect in rough hand specimens; this effect is notable in Triassic sandstones and also in the Permian Nunamara Quarry sandstones.

Controls on the occurrence of authigenic quartz overgrowths are dealt with in Section 7.9 ("Strength and Dimensional Stability").

The detrital quartz comprises strained and unstrained monocrystalline grains, as well as polycrystalline meta-sedimentary lithic fragments, including lutite-grade material (Eggert 1983, Forsyth 1987). Chert and chalcedony grains are volumetrically unimportant (Eggert 1983).

The proportion of quartz in particular sandstone beds will depend on the depositional environment, and upon diagenetic and weathering processes.

Quartz and clay together generally comprise well over 90% of the mineral matter in most sandstones of the Quartz Sandstone Sequence, so that the quartz content is essentially inversely proportional to the clay content (see Appendix One for samples whose quartz and clay contents were both determined in this study). In most cases, detrital feldspar, other non-quartz detrital grains, and ferruginous cements are relatively minor components.

Since fluvial waters generally contain a fairly high concentration of suspended clay and silt in addition to transporting sand grains (Blatt *et al.* 1972,p.61), the relative proportions of quartz sand and clay deposited in fluvial sands will depend upon the degree of winnowing, which is related to stream power (and rate of change thereof, in the case of "dumped" flood sediments).

Since stream power also determines the type of bedding produced in fluvial sand deposits (see Section 7.5.1), it can be inferred that sandstones of a given (fine to medium) grainsize and sorting, and of a given bedding type, will have similar proportions of quartz and clay at the time of deposition, regardless of their geographical or stratigraphic location within the fluvial system. Conversely, sandstones of differing detrital grainsize, sorting and bedding type are likely to have had original differences in quartz and clay content.

Thus, it is likely that some of the variation in quartz/clay content in sandstones as they outcrop today is a result of original variations in their depositional composition, and that these variations can be correlated with grainsize and bedding type.

In general, finer grained Tasmanian Early Triassic sandstones seem to have lower quartz and higher clay contents. This has not been demonstrated statistically, but an example is that the Cobbs Hill Quarry massive sandstone is notably coarser, and has notably less clay, than the Elderslie Quarry massive sandstone.

However, data collected in this study (Appendix One) shows that quartz and clay proportions may also vary markedly between outcropping sandstone deposits of similar grainsize and bedding type. From this, it can be inferred that, while original composition will influence the final mineralogy, major controls on quartz/clay proportions in Early Triassic sandstones outcropping today, and thus on the formation of deposits of high-quartz sandstone, are the diagenetic and weathering processes which have produced varying degrees

of mineral dissolution and authigenic growth of quartz and clays.

This conclusion is strongly supported by the abundant evidence of authigenic mineral growth in the sandstones, in the form of quartz overgrowths, and authigenic clays revealed by Scanning Electron Microscopy and other methods (see Section 7.8.3). Forsyth (1987) notes that Cainozoic weathering has in places selectively destroyed labile grains (eg, feldspars), resulting in more quartzose rocks.

The dissolution and authigenic growth of quartz and clays are discussed in Sections (7.8.3) and (7.9.1 K) below.

7.8.2 Feldspar

Feldspar is generally a minor component in the Quartz Sandstone Sequence. Eggert (1983, quoted by Forsyth 1987 with non-Quartz Sandstone Sequence data removed) found that feldspar comprised 0 - 47% (av. $11 \pm 8\%$) of sandstone grains. Sandstones examined during the present project most commonly contained less than 5% feldspar as a proportion of total mineral matter (ie, including clay).

Eggert (1983) found a low proportion of plagioclase, with microcline and orthoclase being the most abundant feldspar types present. Similar observations were made in the present project. Scanning Electron Microscopy undertaken during the present project showed that the feldspar grains commonly show evidence of partial dissolution (see Plates 7.10, 7.11), suggesting that feldspar content may have been higher at the time of deposition, and that some of the authigenic clays present in sandstone outcropping today may have formed by alteration of detrital feldspar.

The writer has no evidence of any systematic regional (lateral) variations in the feldspar content of the Quartz Sandstone Sequence. However, Forsyth (1987) noted that feldspar (and lithic grains) is more common in bore core from near the top of the lower sandstone dominated interval of the Quartz Sandstone Sequence, and Leaman (1976, 1977) found a similar trend in the Hobart and Brighton quadrangles.

Although feldspar is rarely present in sufficient abundance to cause direct concern from a building stone durability point of view, feldspar abundance is indirectly of concern in that it is related to the abundance of authigenic clays (see Section 7.8.3). The lowest proportions of feldspar will generally be found in the lower parts of the Quartz Sandstone Sequence.

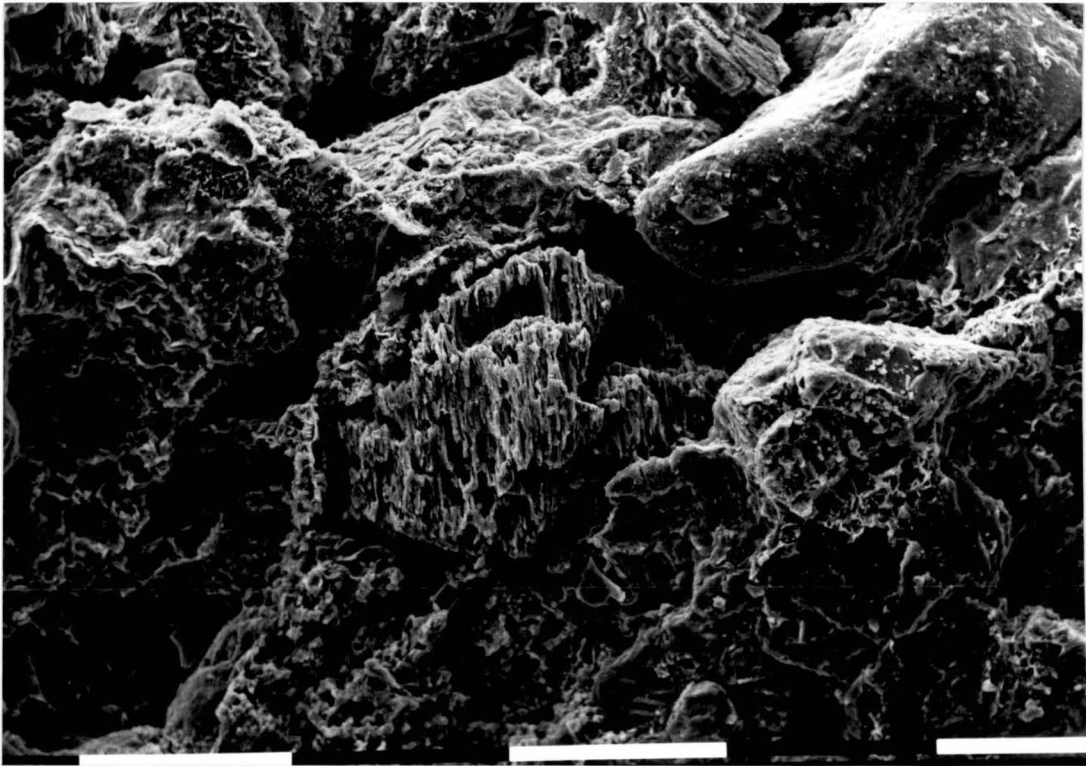


Plate 7.10 Detrital feldspar grain in Early Triassic sandstone from Plummers Quarry (Source 1, specimen PA 1). "Columnar" surface texture indicates partial dissolution controlled by twinning lamellae (the feldspar is probably plagioclase). Note rounded detrital quartz grain at upper right. One scale bar interval = 0.1mm. (S.E.M.)

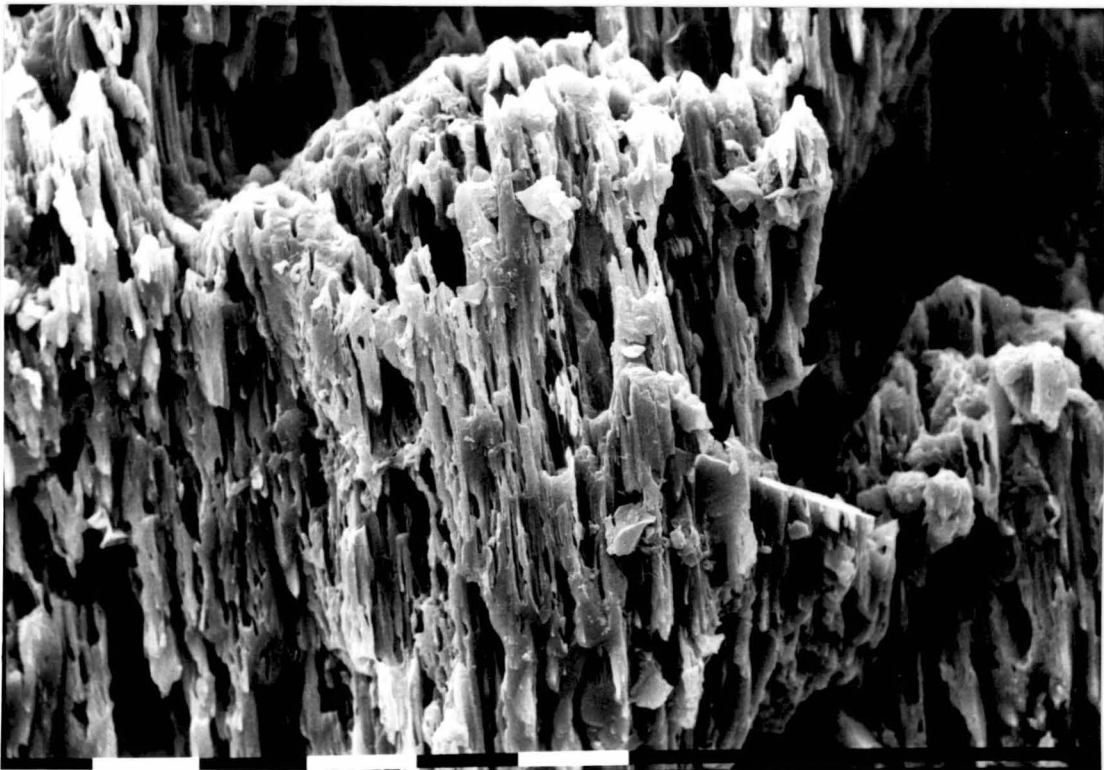


Plate 7.11 Detailed view of feldspar grain in Plate 7.10 (Source 1, spec. PA 1), showing columnar surface texture. One scale bar interval = 10 μ m (S.E.M.)

7.8.3 Clays

Clay is a ubiquitous component of all Tasmanian building sandstones. The clay minerals illite, kaolinite, smectite (montmorillonite), mixed layer illite/smectite, vermiculite, chlorite and halloysite were all identified in Early Triassic Quartz Sandstones during this study.

The clay content of the Early Triassic sandstones ranges from extreme values of 8% to 45% by volume (Appendix One), although the majority of specimens had clay contents in the range 10 - 25% by volume. Apart from macroscopic clay pellets and bands (see Section 7.7.1), the clay occurs in the form of microscopic pellets, as interstitial fillings and as intergranular layers and films. Clay is also commonly a patchy alteration product on and within feldspar grains.

Clays in sandstone may originate in three ways:

- 1) Detrital clay ("allogenic").
- 2) Authigenic clay formed by recrystallisation of earlier detrital clays ("regenerated"). Clays are highly reactive minerals which tend to break down and reform as new clay minerals in order to remain in equilibrium with changing chemical conditions.
- 3) Authigenic clay formed by direct precipitation from porewaters ("neoformed"). These clays may form as a result of the alteration or dissolution of other minerals (eg, feldspar, mica) within the sandstone.

Modern evidence (Wilson & Pittman 1977) has shown that authigenic clay is far more common than previously realised, and all the major clay types are known to be capable of authigenic formation. Wilson & Pittman (*Ibid.*) list the following criteria which can be used to differentiate between detrital and authigenic clays in sandstone, by means of optical and SEM petrography, and X-Ray Diffraction data:

DETRITAL CLAYS

Characterised by broad XRD peaks, with weaker peaks often being absent (indicative of dis-ordering of the crystal lattices with time). Detrital clays may be dispersed as an interstitial or intergranular matrix, or may be concentrated in thin laminae which commonly contain individual particles having a strong preferred orientation which may undulate or "swirl" around sand grains, often showing the effects of burial compaction. Detrital clay also occurs in rounded, commonly elongate aggregates (pellets) of microscopic to macroscopic size (see Plate 7.24).

Under SEM, detrital clay masses show poor crystal shapes (see Plate 7.17), and may be fairly amorphous (due to abrasion during sediment transport, slow partial dissolution of clay crystals after deposition, and deformation of clay masses during burial and as a result of later overburden or tectonic pressures).

AUTHIGENIC CLAYS

Characterised by sharp, narrow XRD peaks, with weaker peaks being present (indicative of well-ordered compositionally-pure crystal lattices which have formed too recently for dis-ordering to have taken significant effect). Neoformed authigenic clays may either fill interstitial pore spaces, or occur as pore-linings (ie, clay "crusts" on sand grain surfaces). They may also occur as pseudomorphous replacements of a parent mineral grain (eg, feldspar), or as fracture and vug fillings.

Regenerated clays may occur distributed in any of the modes of either detrital or neoformed clays.

The most telling indicator of authigenic clays is that, when viewed under the Scanning Electron Microscope, they tend to exhibit very well-formed crystal shapes, which in many cases are of a sufficiently delicate nature to preclude transportation having taken place (the latter applies in particular to features such as the stacking of hexagonal kaolinite "books"). Other clays such as illite do not form such good authigenic crystal shapes, but may have very delicate spine or lath-like projections, which also preclude transport. Authigenic clay masses are also not deformed by compaction of the sediment.

The occurrence of clay flakes growing on other clearly authigenic minerals (eg, quartz overgrowths with well-formed faces) is a good indicator of an authigenic origin. Wilson & Pittman (1977) list a number of further indicators of authigenic clays.

Application of these criteria to optical, SEM and XRD examinations of Tasmanian building sandstones during the present project clearly indicate that, while some clay is of recognisably detrital origin (eg, microscopic pellets and amorphous masses visible by SEM), a large proportion of clay in the sandstones is of a clearly authigenic nature, as indicated by the occurrence of masses having very well-formed, delicate crystal shapes and sharp XRD peaks (see discussions below, and summary of SEM observations in Appendix Twelve).

In a study of Tasmanian Triassic sandstones, Eggert (1983) found clay "cements" and quartz overgrowths to be the most common authigenic minerals in the quartzose sandstones. He identified clay minerals occurring as:

- Recrystallised detrital mudstone fragments and clay matrix.
- Rims on detrital sand grains.
- Pore-lining and pore-filling clays.
- Feldspar grain replacements.

The prevalence of authigenic clays in Tasmanian sandstones poses two important questions from the point of view of high-durability sandstone exploration (and sedimentological studies in general):

- 1) To what extent are the types of authigenic clays present in outcropping sandstones today representative of the types of detrital clays originally deposited in the sandstone? In other words, to what extent are the modern authigenic clays simply detrital clays which have recrystallised ("regenerated") without forming new types of clay, and to what extent are the authigenic clays totally new ("neo-formed") types which were not present (or present in significantly different proportions) when the sandstone was deposited?

Further, where authigenic clays are not simply regenerated detrital clays, to what extent can the occurrence of particular clay types be related to the sandstones original content of other detrital minerals?

- 2) To what extent are the total quantities of clay present in outcropping sandstone today related to the original quantities of detrital clay in the sandstones. Has there been a net gain or loss in clay volume through diagenesis, or has the clay volume remained nearly constant, with only regeneration of existing clay masses occurring?

This question is significant in regard to assessing the possibility of identifying keys to facilitate exploration for low-clay sandstones.

These questions are considered in regard to each of the specific clay types considered below:

(A) Illite

Illite (see Section 2.2.4) is found almost ubiquitously in Tasmanian Early Triassic sandstones.

Numerous XRD analyses (Appendices One & Twelve) during this project yielded both sharp and relatively broad illite peaks, suggesting the presence of both detrital or early authigenic illite, and relatively recent authigenic illite.

Under SEM, authigenic illite characteristically occurs as irregular flakes with (sometimes very delicate) spiny or lath-like projections (see Plate 7.13). The authigenic flakes develop as sheets curling away from the point of attachment on sand grains (see Plate 7.12). Detrital illite flakes may have a ragged appearance with stubby projections dissimilar to the spine-like authigenic projections (Wilson & Pittman, 1977), or may appear more or less amorphous.

SEM results (see Appendix Twelve and Plates 7.12, 7.13) clearly demonstrate the common occurrence of well-formed, delicate authigenic illite flakes in Tasmanian Early Triassic sandstones. The occurrence of detrital illite is harder to demonstrate, but amorphous and ragged flaky masses also observed in many specimens may be detrital.

Detrital illite in sandstones may be derived from reworking of earlier illite-bearing rocks (according to Folk (1974), reworking of rocks such as shales mainly yields illite since other clays, such as kaolinite and smectite, are converted by metamorphic processes into illite, sericite or sometimes chlorite). Thus, it is likely that reworking of sedimentary and meta-sedimentary rocks in the cratonic or unroofed orogenic terrain which formed the main source area for the Early Triassic Quartz Sandstone Sequence provided a proportion of the detrital illite deposited therein.

However, the ultimate source of illite is the weathering of potassium-rich minerals such as muscovite and K-feldspars (Deer *et al.* 1966). The formation of illite requires an environment in which waters are high in K and Al, and low in Mg and Na (Deer *et al.* 1966, Weaver & Pollard 1973,p.19). For this reason, illite formation is favoured by a continental rather than a marine environment. An environment conducive to illite formation will have two main characteristics:

- 1) Parent materials rich in K; muscovite and K-feldspar from acid igneous rocks (Folk 1974) are the most common (where parent materials are basic igneous rocks, Mg ratios will be high and smectites, chlorites or vermiculites will form instead).
- 2) A weathering or diagenetic environment in which incomplete leaching occurs, so that K is not depleted (eg, temperate to arid continental weathering environments) (Folk 1974).

In addition, alkaline waters favour illite formation (Deer *et al.* 1966, Huggett 1984). However, fluvial environments are commonly slightly acidic (pH 5 - 7, Fairbridge *in*

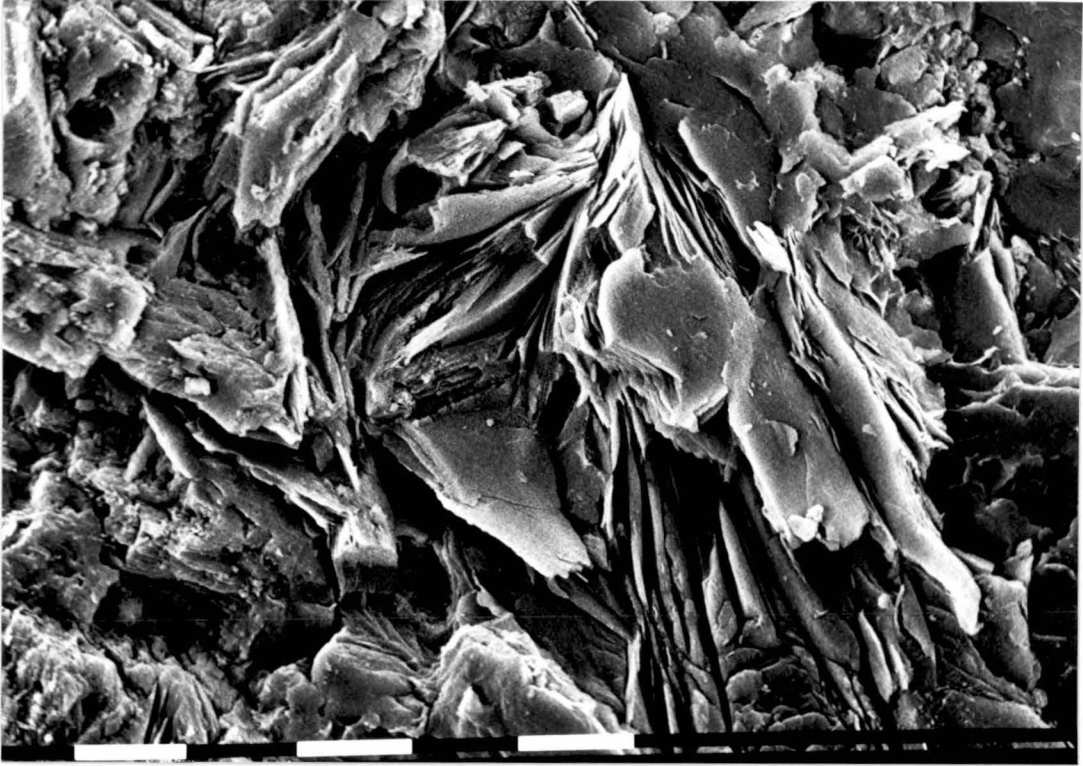


Plate 7.12 Authigenic illite flakes in Early Triassic sandstone from Kingston Quarry (Source 31, specimen KN 1), showing radiating growth habit. One scale bar interval = 10 μm (S.E.M.)

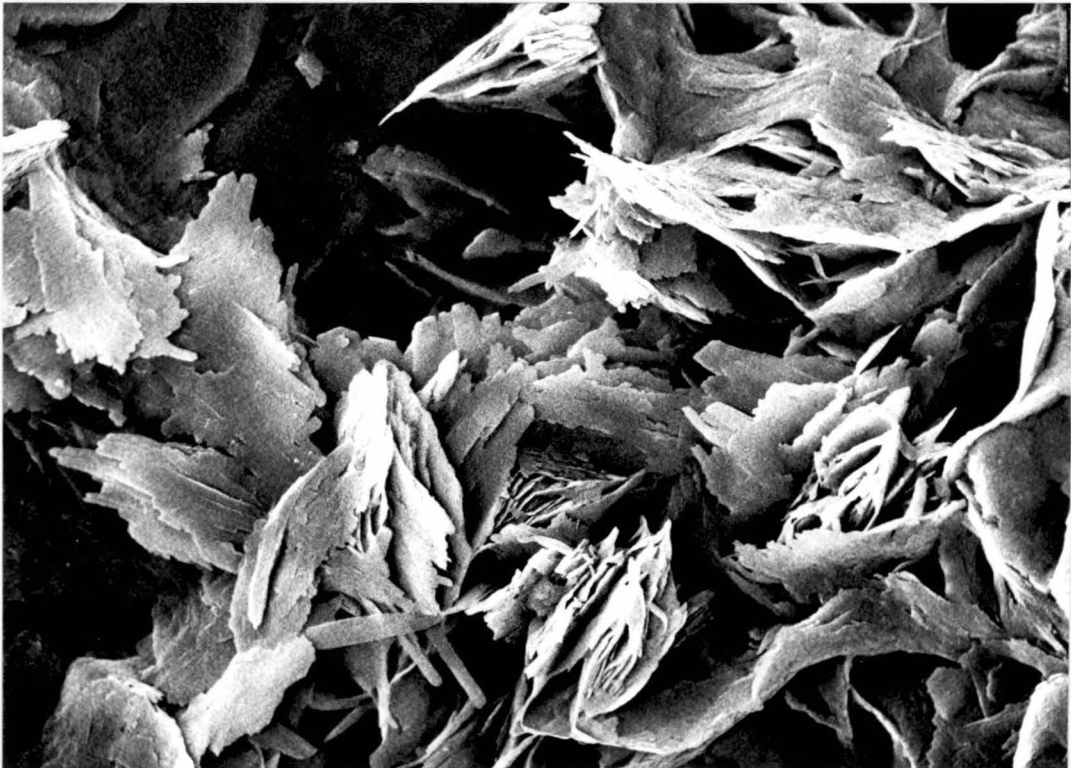


Plate 7.13 Authigenic illite flakes in Early Triassic sandstone from Tea Tree Quarry (Source 13, specimen TT 6), showing delicate lath-like projections. Note abundance of micro-pore spaces between illite flakes. Scale: 20mm = 10 μm (S.E.M.)

Larsen & Chilingar 1967,p.32, Dapples *in* Larsen & Chilingar 1979). It appears that if the two conditions above are well enough fulfilled, illite formation will occur even under slightly acid or neutral conditions. It is also possible that alkaline conditions may develop in poorly drained parts of fluvial systems, such as ponds (Fairbridge *Ibid.* , Fig. 1) and infrequently reworked floodplain soil horizons.

The Quartz Sandstone Sequence was provenanced in a granitic cratonic terrane from which K feldspars (orthoclase and microcline) were being derived (Eggert 1983, Collinson *et al.* 1987, see also Section 7.8.2). Mica was probably also being eroded at the sources. Furthermore, during the Early Triassic the Tasmania Basin is considered to have been a cool temperate or sub-polar arid or seasonally arid fluvial environment (Camp & Banks 1978). Incomplete leaching of weathered source materials would have occurred in poorly drained parts of the arid fluvial basin.

Conditions were therefore ideal for the formation of illite as a result of weathering of granitic source rocks during the Early Triassic. It is highly likely that detrital illite formed in this way was deposited in the Quartz Sandstone Sequence.

The XRD and SEM observations quoted above suggest that at least some of this detrital illite has persisted in the sandstone in a relatively unaltered state. There is evidence that, once formed, illite may be a very stable mineral. For instance, Folk (1974, quoted above) has noted that illite may remain stable during sedimentary reworking processes, and Morad & AlDahan (1987) have noted the presence in Proterozoic sandstones of illites which have apparently remained stable since their (diagenetic) formation.

There is also clear evidence (see above) of authigenic illite in the Quartz Sandstone Sequence. Some of this could be regenerated detrital illite. However, both mica (including muscovite) and K-feldspars (orthoclase, microcline) are present in the Sequence (Eggert 1983). While rarely abundant, a small proportion of these minerals was noted in virtually every specimen studied during the present project.

Feldspars, particularly orthoclase, in Early Triassic sandstones very commonly show some alteration to clay under the optical microscope, and a number of partly altered feldspar grains having "eroded" surface textures were noted during SEM observations (Plates 7.10, 7.11). It appears probable that diagenetic or weathering alteration of the K-feldspars and micas has given rise to the production of neoformed authigenic illite. Previous workers, such as Huggett (1984), Morad (1984) and Morad & AlDahan (1987) have demonstrated that authigenic illite may form by alteration of K-feldspar and muscovite grains in sandstones.

The timing of illite authigenesis in the Quartz Sandstone Sequence is of interest. Alkaline groundwater conditions (pH 7 - 9) may occur during uplift and onset of a near-surface weathering environment influenced by meteoric waters (Fairbridge, *in* Larsen & Chilingar, 1967, p.32). Thus, at least some of the formation of authigenetic illite is likely to have occurred during Cainozoic weathering which, as noted by Forsyth (1987), has in places destroyed labile grains (feldspars) in the Quartz Sandstone Sequence. Under these conditions, partial leaching by groundwaters would result in retention of sufficient K from breakdown of the feldspars to form illite.

Authigenic Illite may also form through the breakdown of feldspars, kaolinite and smectite in response to the elevated temperatures of deep burial (Folk 1974, Siever 1986). Diagenetic studies (eg, Hower *et al.* 1976) have established that such diagenetic illitisation begins at about 50° C, usually more than 1000 metres below the surface. However, Siever

(*Ibid.*, p. 243) suggests that even under high heat flow conditions burial in excess of two kilometres would be necessary to achieve this effect to any significant degree. Since Tasmanian Triassic sandstones are thought to have been buried to depths of between one and three kilometres (see Everard, *in* Turner & Calver, 1987, p.144), this mechanism probably played some part in the production of diagenetic illite.

(B) Kaolinite

Kaolinite (see Section 2.2.4) is very common in Tasmanian Early Triassic sandstones.

In numerous XRD analyses during this project (Appendices One & Twelve) there was a notable tendency for the kaolinite to yield narrow, sharp peaks indicative of a relatively recent authigenic origin. A smaller proportion of XRD analyses yielded broad peaks indicative of poorly ordered crystal lattices (detrital or early authigenic kaolinite?).

Authigenic kaolinite is readily identifiable under SEM, occurring as clean-edged pseudo-hexagonal crystals or plates (Wilson & Pittman 1977). The plates occur singly, in neat stacks ("books"), or as masses of overlapping plates coating sand grains. Authigenic kaolinite is most commonly pore-filling, but may also occur as pore-linings.

Using these criteria, authigenic kaolinite was identified in a large number of Early Triassic sandstones (Appendix Twelve). It is commonly found on the surface of authigenic quartz overgrowths, indicating kaolinite authigenesis at a late stage, after quartz authigenesis (see Plates 7.14, 7.15).

Detrital kaolinite is less easy to identify by SEM, although its presence (or that of early-diagenetic kaolinite) is suggested by XRD results (above). Probable detrital kaolinite has been identified in specimen V3 (Ventenat Point Quarry): XRD analysis indicates a clay matrix dominated by detrital kaolinite, and detrital clay pellets visible under SEM show vaguely hexagonal plate outlines in predominantly amorphous clay masses (see Plates 7.16, 7.17).

Thus, there is good evidence for the occurrence of both detrital and authigenic kaolinite in Early Triassic sandstones.

Kaolinite is a relatively simple clay which is subject to little compositional variation (Deer *et al.* 1966), and it forms when exchangeable cations such as K, Mg, Ca, or Na are not available, commonly as a result of strong leaching.

Since kaolinite easily breaks down during deep burial and incipient metamorphism (Folk 1974), reworking of kaolinite-bearing rocks is normally only a minor source of detrital kaolinite. Also for this reason, the preservation of some probable detrital kaolinite in Tasmanian Early Triassic sandstones is an indicator of a comparatively shallow maximum burial depth (ie, only a few kilometres).

Most detrital kaolinite is derived from the weathering of all types of feldspars, or from other silicates (most commonly derived from acid rocks such as granites), under acid chemical conditions (Deer *et al.* 1966) in which strong leaching removes both K and Mg (Folk 1974). Thus, kaolinite may form by weathering of the same source rocks that illite (and even smectite) are formed from, but under strongly leaching conditions as opposed to the incomplete leaching required for the latter two clays to form. While cool conditions inhibit kaolinite formation (Folk 1974), sufficient leaching and drainage will allow

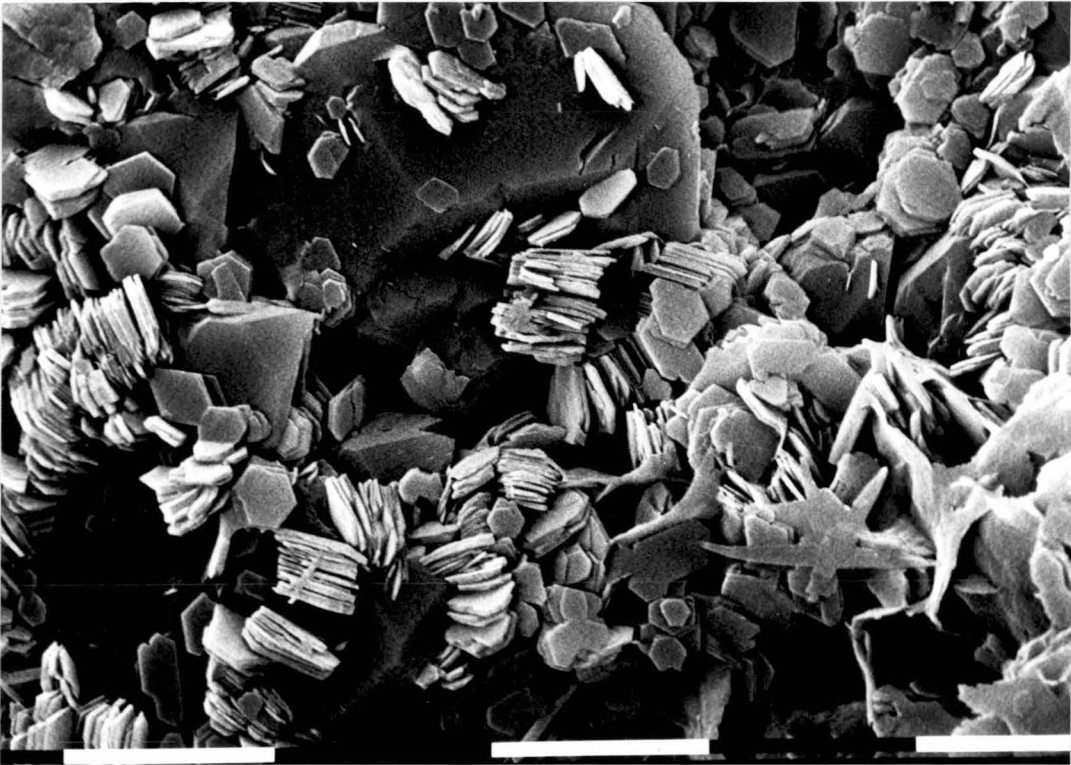


Plate 7.14 "Books" and individual pseudo-hexagonal plates of authigenic kaolinite in Early Triassic sandstone from Okehampton Quarry (Source 14, specimen Oak 2). The kaolinite is growing upon (and is therefore later than) well-formed authigenic quartz faces. One scale bar interval = 10 μm (S.E.M.)

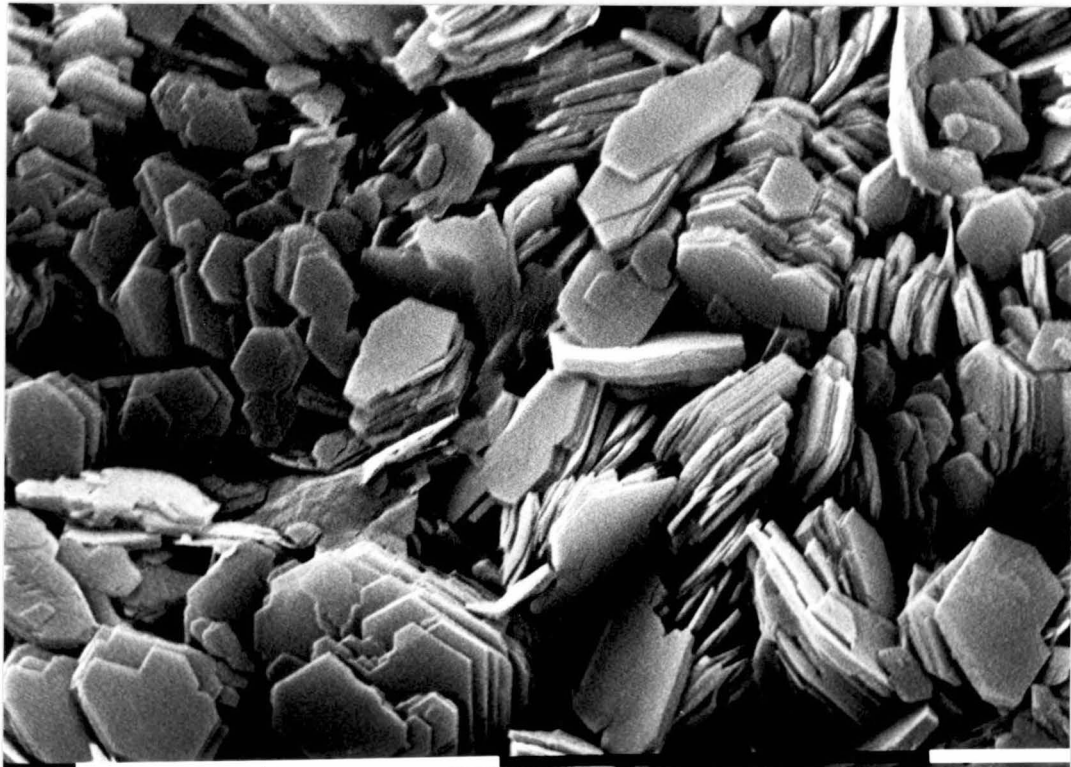


Plate 7.15 Authigenic kaolinite aggregate in Early Triassic sandstone from Okehampton Quarry (Source 14, specimen Oak 1). Note abundance of micro-pore spaces between kaolinite flakes. One scale bar interval = 10 μm (S.E.M.)

kaolinite to form even in a cool climate (Davis 1964). Kaolinite is stable in continental, fresh-water environments, and in soils undergoing weathering.

As noted in the discussion of illite above, the Early Triassic Quartz Sandstone Sequence sediments were provenanced in a dominantly granitic terrain, so that suitable feldspar and mica source materials for formation of detrital kaolinite were available. Whilst the cool climate and arid or seasonally arid nature of the fluvial basin as a whole (Camp & Banks 1978) favoured the production of illite from these source materials, some quantities of kaolinite would at the same time be formed in the better drained (and so better leached) parts of the fluvial system, under probably slightly acid fluvial conditions (Dapples *in* Larsen & Chilingar 1979).

Slow dissolution of some kaolinite may have occurred due to increased temperatures during the deeper phases of burial of the Quartz Sandstone Sequence (Folk 1974), resulting in diagenetic formation of chlorite or illite if Fe, Mg or K derived from concurrent slow breakdown of smectite (Folk 1974) and/or detrital igneous mineral grains were present in the pore-waters. However the relatively shallow burial depths and persistence of detrital kaolinite in outcropping sandstones implies that any such effect only occurred on a small scale.

The SEM evidence described above indicates that the major phase of kaolinite authigenesis probably occurs at late stages of uplift and weathering, after quartz authigenesis, when opportunities for strong leaching of detrital feldspars and micas, and of other clays, are once again presented. Evidence observed in this project indicates two environments in which significant late-stage kaolinite authigenesis may occur:

1) Sub-surface groundwater flushing zones

The discussion of illite (above) suggested that late-stage illite authigenesis occurs under sub-surface incipient weathering conditions, as a result of breakdown of feldspars and micas under conditions of partial leaching by alkaline groundwaters (Fairbridge, *in* Larsen & Chilingar 1967, Fig 4). These conditions would apply in zones of relatively unfractured, lower porosity sandstone, with slow flushing of the groundwaters.

However, under certain circumstances zones of increased flushing-through of near-surface groundwaters may result in strong leaching of feldspars, micas, and any other clays present, with the result that these minerals are depleted and kaolinite precipitated. Rapidly-flushing near-surface groundwaters derived from rainwaters and surface waters are likely to be of neutral or slightly acid chemistry (Fairbridge, *in* Larsen & Chilingar 1967, Figs 1 & 4), which is also conducive to kaolinite formation. Increased groundwater flushing would be expected in aquifers produced by beds or zones of high porosity or intense fracturing.

Morad (1984) and Morad & AlDahan (1987) documented the formation of authigenic kaolinite from feldspars and micas, and Huggett (1984) showed that this may occur under acid groundwater conditions. Kantorowicz (1984) has related the authigenesis of kaolinites (kaolinite) in Jurassic North Sea sandstones to introduction of oxygenated fresh surface waters during a period of regression.

Most significantly, studies of the British Triassic Sherwood Group fluvial sandstones by Burley (1984) showed that, while modern groundwaters in most of the sandstone are close to neutral pH, the sandstones of the Wessex Basin have been extensively

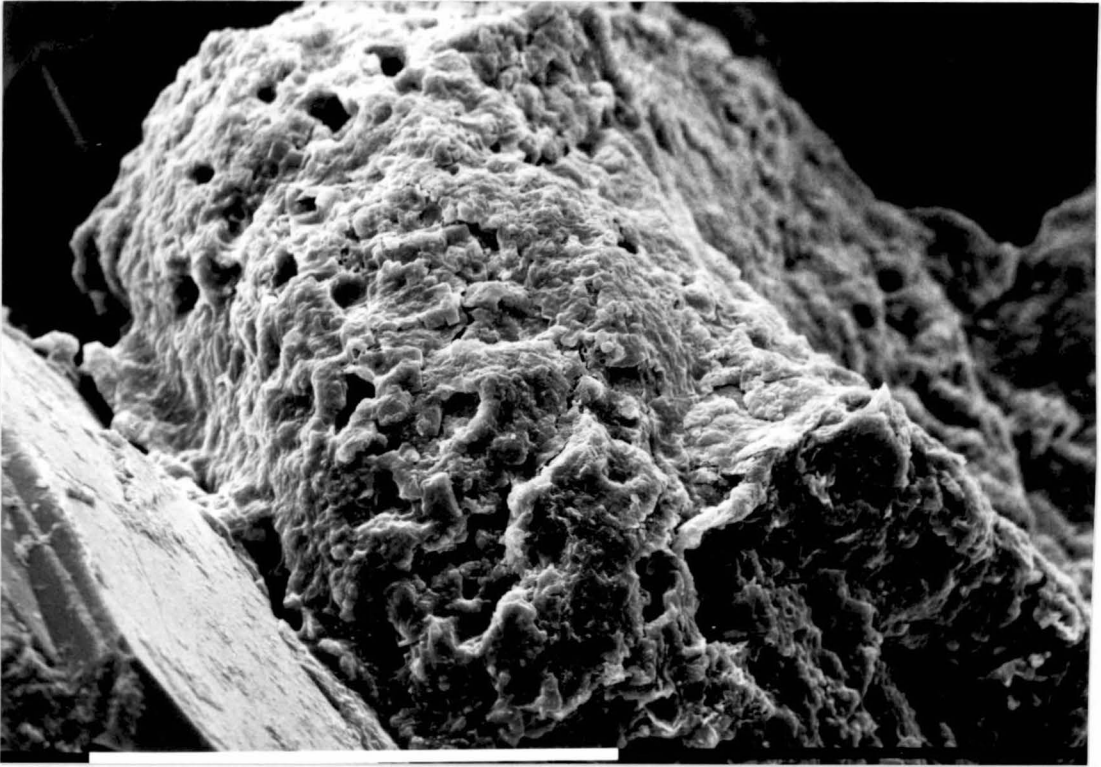


Plate 7.16 Detrital clay pellet in Early Triassic sandstone from Ventenat Point Quarry (Source 12, specimen V 3). Dominantly kaolinite composition of pellet is suggested by XRD analysis of specimen, and presence of degraded hexagonal flakes (see Plate 7.17 below). One scale bar interval = 0.1 mm (S.E.M.)

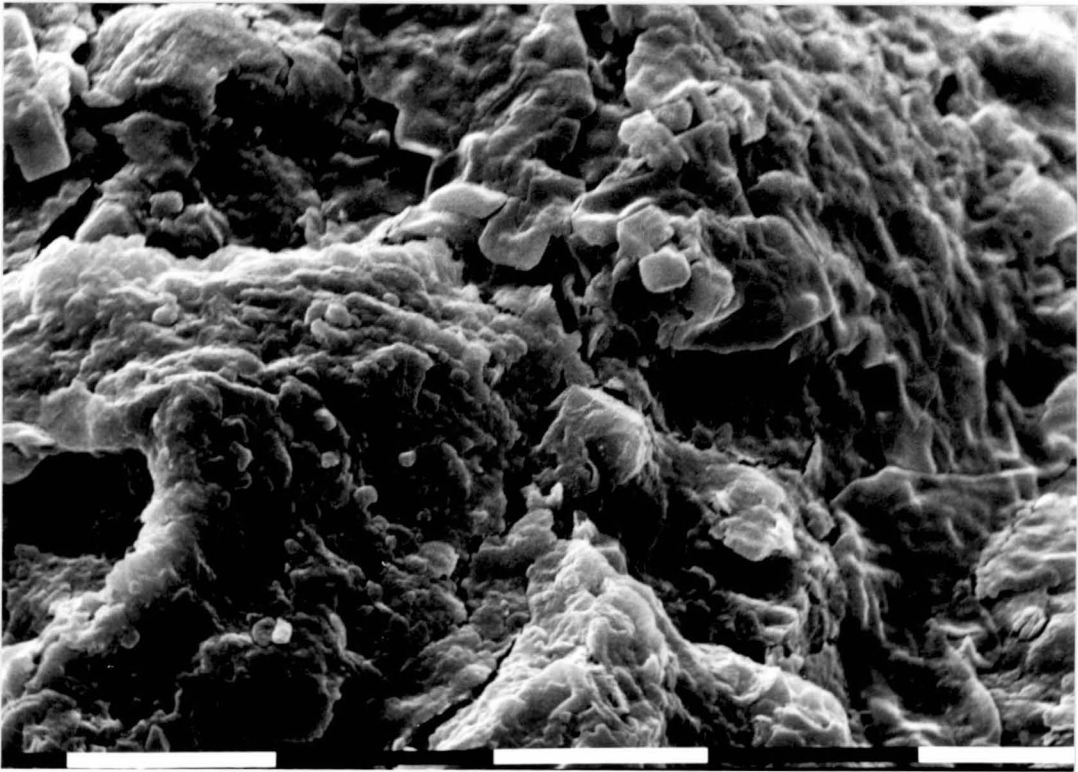


Plate 7.17 Detail of detrital kaolinite clay pellet in Plate 7.16 above (Ventenat Point Quarry, Source 12, specimen V 3), showing degraded, vaguely hexagonal kaolinite flakes in amorphous mass. One scale bar interval = 10 μ m (S.E.M.)

modified as a result of infiltration of acidic groundwaters in the South Devon aquifer. These acidic aquifer groundwaters have produced abundant authigenic kaolinite (kaolinite) from the *in situ* breakdown of feldspars.

In Australia, Conolly (1965) and Slansky (1977) have noted that authigenic kaolinite is the dominant clay mineral in sandstone aquifers and in more permeable sandstones of the Great Australian Artesian Basin. Slansky found that in less permeable horizons of the sandstone units he studied (the Jurassic Pillaga Sandstone and the Cretaceous Horray Sandstone), smectite was the dominant clay mineral.

Arditto (1983) concluded that authigenic kaolinite in the Great Australian Basin sandstones formed from alteration of detrital feldspars and micas as a result of leaching by low pH (acid), CO₂ - charged groundwaters. Arditto notes that a warm tropical environment is not necessary for this process, and Davis (1964) showed that the rate of precipitation and groundwater flow is more important than temperature in such processes.

In the present study, detailed clay analyses were undertaken on a Mines Département cored drill hole (DDH "Thorpe") through the Quartz Sandstone Sequence near Bothwell (Sharples 1984, reproduced in Appendix 11; see also Fig. 7.9). An intensely fractured zone, considered to be a major aquifer, occurs between 101 and 107 metres. In a zone extending from 90 to 125 metres depth, concentric about this fracture zone, illite and smectite are notably depleted in relation to the rest of the hole, and kaolinite is consistently more abundant than elsewhere (see Appendix 11 figure). The kaolinite in this zone gave consistently sharp XRD peaks, indicating an authigenic character.

The indication from this data is that rapid flushing of groundwaters through the fracture zone has extensively leached illite and smectite (and probably detrital feldspar and mica), resulting in formation of authigenic kaolinite.

Further evidence is yielded by the Buckland Quarry (Source 28). As noted in Section (7.6.4), within four metres or more of the natural surface this deposit is characterised by sharply delimited zones of strong Liesegang ring patterning, laterally interspersed with zones of grey/white stone completely free of iron staining (see Plate 7.6).

As expounded in Section (7.6.4), the precipitation of Liesegang rings is thought to be a near-surface weathering-related phenomenon involving iron-rich groundwaters moving through the sandstone towards the outcrop surface. The close proximity of unstained and strongly iron-stained zones implies that the iron-rich groundwaters moved preferentially through the zones which are now stained. It is not known whether this preferential movement of groundwater through certain zones was due to pre-weathering porosity differences between the stained and unstained zones, to the presence of sub-surface fissure zones beneath the stained zones, or to some other cause.

Fresh sandstone specimens from the iron stained zones have much higher total clay contents, and notably higher kaolinite proportions, than the unstained zones (Appendix One). Kaolinite in both zones yielded sharp XRD peaks, indicating authigenic origin.

Again, this data indicates that kaolinite has formed authigenically as a result of near-surface groundwater processes, and that kaolinite production was greatest in those zones which experienced the strongest flushing-through of groundwaters.

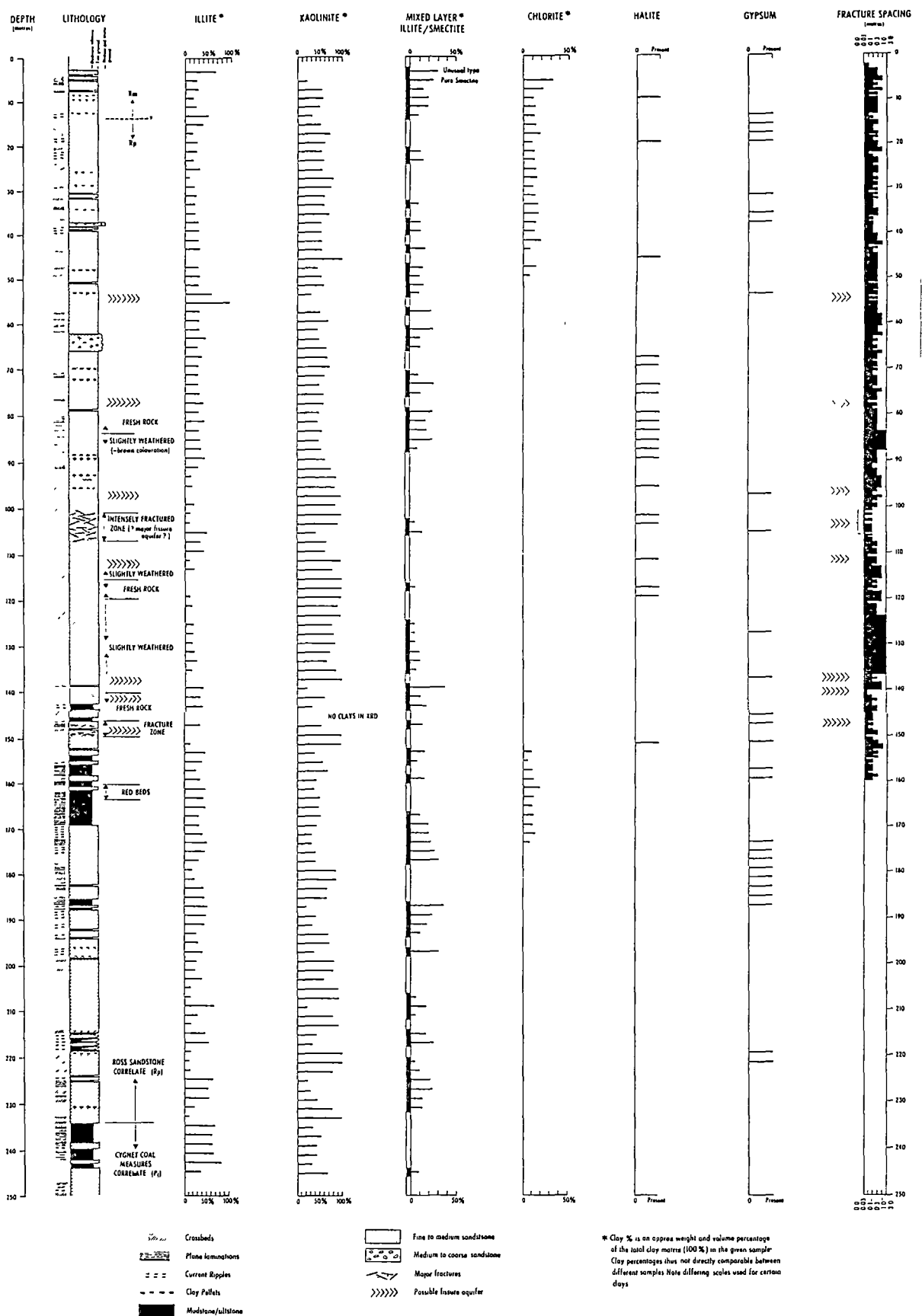


FIGURE 7.9 Bothwell Drillhole "Thorpe" (Sharples 1984, see Appendix 11): Distribution of clay types through the dominantly sandstone interval of the Early Triassic Quartz Sandstone Sequence (Rp).

2) Surface weathering

The other environment in which significant late-stage kaolinite authigenesis is likely to occur is at the surface of outcrops. Regular and thorough flushing through of neutral to slightly acid rainwaters and surface waters would cause strong leaching within a metre or two of outcrop surfaces, resulting in weathering of feldspars, micas and other clays, and precipitation of kaolinite. This effect would be strongest in warm humid climates, but can be expected to occur to some extent in the temperate, but wet, Tasmanian climate.

As a result of studies of authigenic kaolinite in Devonian sandstones in New South Wales, Conolly (1965) concluded that the kaolinite may form both in the sub-surface and as a surface outcrop weathering effect. In both cases, kaolinite formed at the expense of illite. However, Arditto (1983) concludes that the surface kaolinisation effect is less important than sub-surface precipitation of authigenic kaolinite.

At the Elderslie Quarry (Source 26), detailed XRD analysis was undertaken on a face exposing stone from the natural outcrop surface to a depth of 3.5 metres. Details are given in Section (7.11.1). Below 1.5 metres depth, minor amounts of smectite are present and kaolinite is completely absent. From 1.5 metres depth up to the outcrop surface, there is a complete depletion of smectite and a progressive increase in kaolinite content. Although only small quantities of kaolinite are present, the surface smectite-depletion and kaolinite-precipitation effect is quite distinct (see Fig. 7.20). Feldspar occurs in the section, in minor quantities.

A similar surface effect is documented at the Cobbs Hill Quarry (Source 23, see Appendix One), where surface samples yielded significantly higher kaolinite contents (and lower illite contents) than did fresh samples from 0.6 metres or deeper below the natural outcrop surface.

(C) Halloysite

Halloysite is a kandite (ie, related to kaolinite), and occurs rarely in Tasmanian Triassic sandstones. In this project, it was only found in sandstone from Cobbs Hill Quarry. The clay was identified by means of both XRD and SEM (see Plate 7.18).

Halloysite is a swelling clay. In its hydrated form, it consists of "kaolinite" layers with interlayers of water molecules, and typically takes the form of cylinders or rods. Dehydration may result in splitting, collapsing or unrolling of the tubes (Grim 1962). Temperatures of 400°C are necessary for complete dehydration, and most naturally occurring halloysite is in a stable partially hydrated form (Grim 1962) which probably presents few problems from a building stone durability point of view.

SEM examination of the Cobbs Hill sandstone (Plate 7.18) shows that the halloysite occurs as very thin, delicate rods. Their delicate morphologies are a clear indication of authigenic origin.

The origin of the Cobbs Hill halloysite is unclear; however its rarity implies that it is not an important consideration in the development of exploration models for building sandstone.

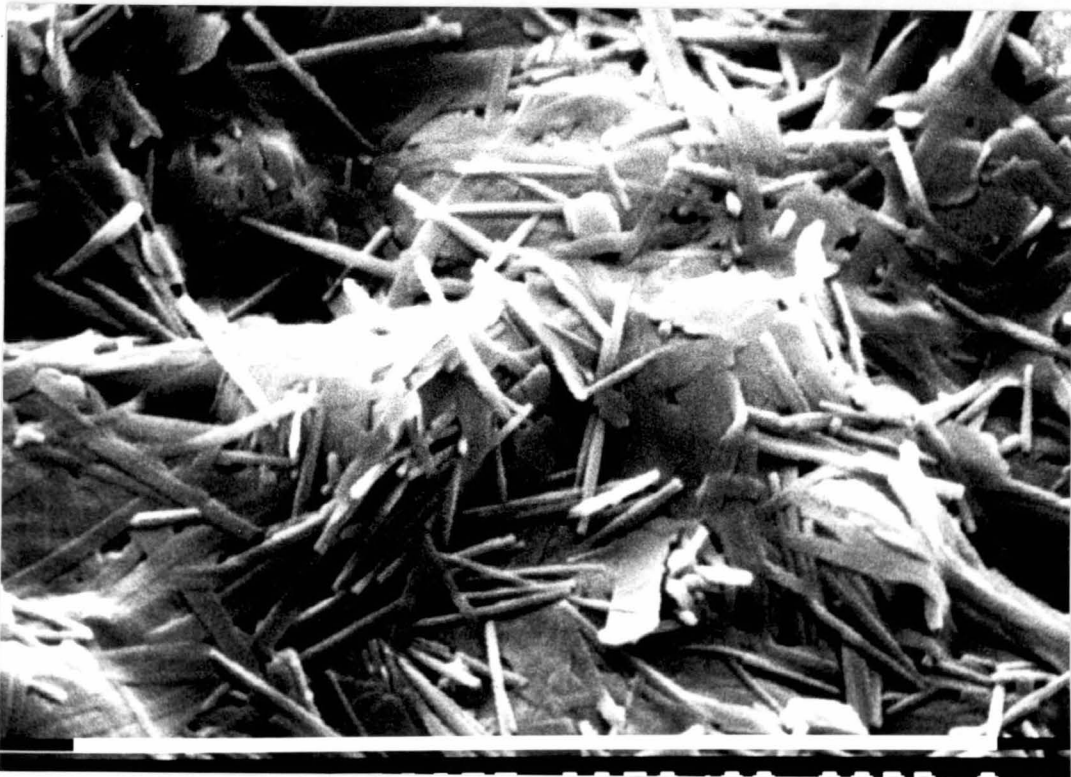


Plate 7.18 Authigenic halloysite rods in Early Triassic sandstone from Cobbs Hill Quarry (Source 23, specimen Cobb 2).
One Scale bar interval = 10 μm (S.E.M.)

(D) Smectite and mixed layer illite/smectite

Smectite (probably montmorillonite; see Section 2.2.4) or mixed layer illite/smectite is relatively common in Tasmanian Early Triassic sandstones, having been found in varying proportions in about half of the sandstone specimens analysed in this work.

Pure smectite and mixed layer illite/smectite can be differentiated by their differing XRD peak shapes (Thorez 1975), and both types have been identified in Tasmanian sandstones. Mixed layer illite/smectite appears to greatly dominate over occurrences of pure smectite (Sharples 1984, see Appendix 11). Mixed layer varieties tend to give broad peaks which makes it difficult to assess whether they are authigenic or not on the basis of XRD (Wilson & Pittman 1977). After glycolation (see Appendix Three) the smectite peak may become relatively sharp, which may be indicative of an authigenic origin.

Under SEM, authigenic smectite forms crinkly coatings on sand grains, or forms delicate cellular "honeycomb" structures in which individual crystals cannot be distinguished (Wilson & Pittman 1977). Mixed layer illite/smectite takes similar morphologies to either smectite or illite, depending on which clay type is dominant. Dominantly smectite types may take a typical honeycomb smectite form with short digitate projections typical of illite projecting from the smectite plates. Authigenic smectite or illite/smectite tends to grow as pore linings rather than pore fillings.

Dis-aggregated or detrital smectite is difficult to identify on the basis of morphology; Neumann (1976) says that individual smectite flakes may take the form of lath-shaped (or even hexagonal) particles. Presumably detrital or partly altered early diagenetic smectite would commonly occur as more or less amorphous masses.

Using these criteria, SEM studies of Early Triassic Tasmanian sandstones (Appendix 12) have demonstrated the presence of authigenic smectite and mixed layer illite/smectite in a number of cases (see Plates 7.19, 7.20). The authigenic smectite has been found growing on authigenic quartz overgrowths, indicating late-stage authigenesis. Detrital smectite has not been positively identified as such, but the relatively broad XRD peaks which are commonly produced even after glycolation are likely to represent detrital or early diagenetic smectite.

The most common source of smectite in the sedimentary environment is the breakdown of basic igneous rocks, ash or glass (Deer *et al.* 1966, Folk 1974). (However, note that acid or intermediate volcanics are not ruled out as a smectite precursor; Summa & Verosub (1987) found that smectite is common as an alteration product of both rhyolitic and basaltic Miocene to Recent North American pyroclastic deposits.)

Whilst smectite varieties have not been differentiated in the Quartz Sandstone Sequence, the most common type in nature is Ca-montmorillonite (Deer *et al.* 1966). Formation of Ca-montmorillonite in continental weathering environments requires the following conditions (Deer *et al.* 1966, Folk 1974):

- 1) Abundant Mg (the most important single factor).
- 2) Ca available.
- 3) K low (may form mixed layer illite/smectite if small quantities present).
- 4) Alkaline weathering conditions.
- 5) Poorly leached weathering conditions, causing retention of Mg and Ca in the system (kaolinite will form in strongly leached environments where Mg is removed).

Pyroxenes are the most abundant minerals in basic rocks which fulfill the chemical requirements for smectite formation. Diopside ($\text{Ca Mg Si}_2\text{O}_6$) and augite

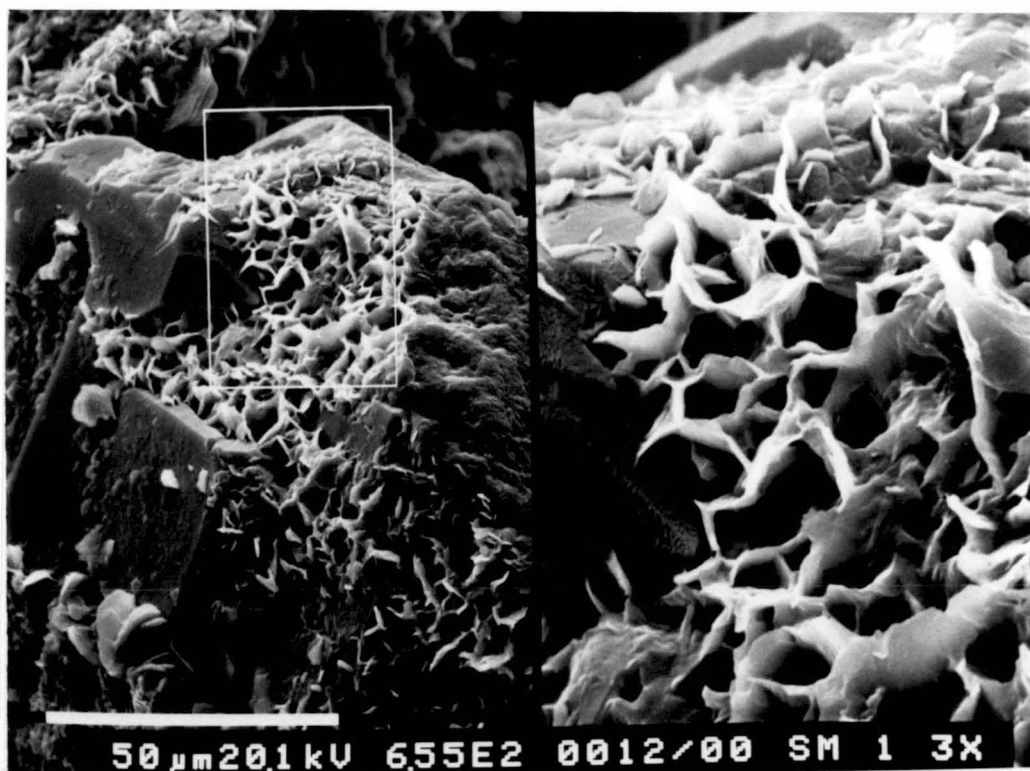


Plate 7.19 Authigenic smectite growing on (earlier) authigenic quartz overgrowths in Early Triassic sandstone from Kangaroo Point Green Sandstone Quarry (Source 4, specimen SM 1). One scale bar interval = 50 μm (S.E.M.)

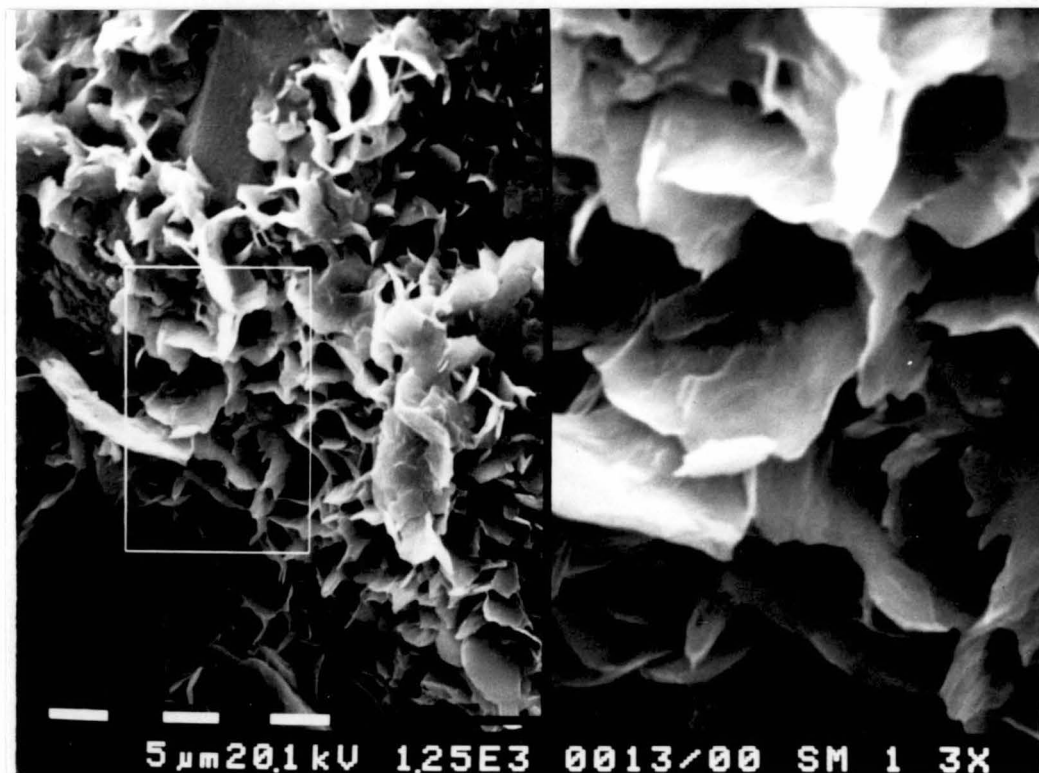


Plate 7.20 Authigenic mixed layer illite/smectite in Early Triassic sandstone from Kangaroo Point Green Sandstone Quarry (Source 4, specimen SM 1). Honeycomb habit is characteristic of smectite, while delicate lath-like projections indicate illite content. One scale bar interval = 5 μm (S.E.M.)

($\text{Ca}[\text{Mg,Fe,Al}][\text{Al,Si}_2\text{O}_6]$) both occur in basic rocks, and would form Ca-montmorillonite upon poorly-leached weathering. Olivine is also a possible smectite precursor, although lacking in Ca. Calcium-enriched, K-free plagioclase varieties (labradorite and bytownite) dominate over Na-enriched plagioclase in most basic igneous rocks (Berry & Mason 1959), and would provide a further input of calcium.

As with illite, poorly drained parts of the arid or seasonally arid Early Triassic Tasmania Basin (Camp & Banks 1978) would have provided an ideal physical environment for smectite to form from the breakdown of suitable parent materials. Such poor drainage might be found in ponds or soil horizons and sub-surface deposits of infrequently reworked floodplain deposits.

Suitable parent materials for the production of illite in the basin were provided by drainage from eroding granitic source areas to the west and northwest (Collinson *et al.* 1987). However, the supply of basic igneous materials from that source was probably minor (*Ibid.*), and insufficient to account for the abundance of smectite in the Quartz Sandstone Sequence.

There is evidence of volcanism near Tasmania through parts of the Permian and Triassic. Bentonite (smectite-rich) beds occur in the Mid-Permian Berriedale Formation at Hobart and Maria Island (Clarke, *in* Burrett & Martin 1989, p.303), and are considered to be formed from volcanic ash derived from distant volcanism. In the Late Permian; upper parts of the Ferntree Formation south of Woodbridge contain high proportions of silicic volcanic ash, including cusped glass shards, indicative of contemporary volcanism close to southeast Tasmania (Banks, *Ibid.*, p.293, Clarke, *Ibid.*, p.307). In the Latest Permian Cygnet Coal Measures (immediately underlying the Quartz Sandstone Sequence), variation in feldspar content suggests volcanism southeast of Tasmania (Banks, *Ibid.*). Finally, in the Mid to Late Triassic, after deposition of the Quartz Sandstone Sequence, volcanism was intense and nearby, with basalts being extruded in northeastern Tasmania, and volcanic lithic clasts becoming an important component of the sandstones (Forsyth *in* Burrett & Martin 1989).

Collinson *et al.* (1987) attribute the Mid-Late Triassic volcanic activity to an active calc-alkaline complex along the Pacific margin (east of Tasmania) of Gondwanaland. The evidence of earlier Permian volcanism in the same general direction during the Middle and Late Permian suggests that the volcanism may also have been occurring, perhaps at lesser intensity, during the intervening Early Triassic period.

Fluvial drainage during the Early Triassic was from the cratonic areas to the west, and it was only in the Mid-Late Triassic that drainage directions changed in the Tasmania Basin, bringing an influx of river-borne volcanic detritus from the volcanic complex to the east (Forsyth *in* Burrett & Martin 1989).

It is therefore hypothesised that the source of (probably basic) volcanic materials which are the ultimate source of smectite in the Quartz Sandstone Sequence was atmospheric transport of volcanic ash and dust particles from active volcanic sources in a direction generally east of Tasmania. The fact that the highest concentrations of smectite yet measured in Early Triassic sandstones occur in southeast Tasmania (see Fig. 7.10) is suggestive of a source area to the east or southeast.

The deposition of bentonite deposits (dominantly smectite clay beds) from atmospheric transport of volcanic ash and dust from distant volcanoes is well documented (eg, Pacey 1984). Sampling of modern volcanic ash clouds (eg, Rose *et al.* 1980) has shown that they consist of vapour and fluid aerosols (eg, sulphuric acid), volcanic glass particles, and

crystalline fragments. Summa & Verosub (1987) found that recent Hawaiian basaltic pyroclastic deposits comprised 90 - 95% basaltic glass and 5 - 10% basaltic rock fragments and crystal fragments (pyroxene, olivine, plagioclase and other minerals). Such glass and crystalline ashes are suitable smectite precursors, and Summa & Verosub (1987) found montmorillonite as a major alteration product of their Hawaiian pyroclastic deposits.

The volcanic sources must have been sufficiently distant, in the opposite direction to prevailing Early Triassic drainage, that little or no volcanic debris was introduced into the basin by fluvial transport, and no ash particles large enough to survive diagenesis unaltered were deposited from the atmosphere. This is implied by the rarity or absence of identifiable volcanic clasts in the Quartz Sandstone Sequence.

Atmospheric volcanic dust falling onto the Tasmania Basin from distant sources would be predominantly of very fine grain size. Fine dispersions of dust would settle over wide areas of the basin, and then be subject to repeated reworking by fluvial processes. As a result, concentrated bentonite bands would not have formed.

The volcanic dust would have suffered surface weathering, and in the more poorly drained soil horizons and other parts of the arid fluvial basin the pyroxene, olivine and plagioclase in crystalline dust particles, and volcanic glass particles of equivalent composition, would have been incompletely leached to form smectite, which would ultimately be redistributed and deposited as detrital smectite dispersed through significant volumes of sand.

Continuing alteration of any remaining volcanic dust clasts to smectite would probably occur during early stages of burial. The probable very fine grain size and labile nature of the volcanic dust particles means that it is likely that the dust would quickly (prior to deep burial) be almost completely altered to clay, leaving little direct evidence of its volcanic origin (such as recognisable glass shards), and causing a significant increase in the total clay content of the sandstones soon after deposition (see Section 7.8.1, and Figs 7.12, 7.13).

Pacey (1984,p.51) notes that detrital smectites derived from continental soil zones usually tend to be of poor crystallinity and exhibit extensive mixed layering. Similarly, Schultz (1978) found that pyroclastic material deposited and weathered on land tended to form mixed layer illite/smectite, due to the relatively open nature of the chemical system. Pure smectite was found in bentonite bands formed from closed system pyroclastic bands deposited in marine basins.

Given that granite-derived K-feldspars, intermixed with the volcanic dust in the Early Triassic fluvial sands, were concurrently altering to illite (see illite discussion above), it is highly likely that much of the initial smectite, formed by alteration of pyroxene, quickly altered to mixed layer illite/smectite due to addition of K in the pore waters derived from concurrently weathering K-feldspar grains. Pure smectite would be more likely to be preserved in deposits having a much higher than usual concentration of volcanic dust, and so was probably rare in the Early Triassic depositional environment.

Vulcanism may have been inactive or more distant during the deposition of the Permian Lower Freshwater Sequence, resulting in the Permian Nunamara sandstone being free of smectite.

During the deeper stages of burial of the Quartz Sandstone Sequence, some breakdown of smectite can be expected due to increasing temperatures (Folk 1974, Hower *et al.* 1976, Siever 1986). (Smectite is generally absent from sediments older than Mesozoic (Ollier

1969,p.257), due to its tendency to break down upon deep burial.)This process was probably relatively minor, due to the relatively shallow maximum burial depths of the Quartz Sandstone Sequence (One to three km? See Everard, *in* Turner & Calver 1987,p.144). See also the discussion of illite burial diagenesis above.

Such deep burial diagenesis as occurred would probably have involved minor breakdown of both detrital K-feldspars and the smectite layers of the detrital illite/smectite. The products of the smectite breakdown, combined with K released from the feldspar, would lead to formation of diagenetic illite, whilst the Mg released from the smectite would produce diagenetic chlorite (Folk 1974, Siever 1986). The result would be the production of authigenic illite and chlorite, and authigenic mixed layer illite/smectites having a higher proportion of illite layers than did the original detrital illite/smectite.

However, the SEM data obtained during this project (Appendix 12) showed that much of the authigenic smectite (most of which appears to be mixed layer illite/smectite) is of relatively recent origin, since it commonly has grown on the surfaces of authigenic quartz overgrowths and therefore post-dates quartz authigenesis.

It is unlikely that the late stage authigenesis of smectite or mixed layer illite/smectite results from further weathering of remanent detrital basic volcanic materials, since these most probably were completely altered to smectite during the initial deposition and shallow burial phases.

The mode of late stage smectite and mixed layer illite/smectite authigenesis is unclear. The following mechanisms are postulated, but further investigation of this problem will be necessary:

- 1) It is thought that smectite breaks down in strongly leached surface and near-surface zones subject to rapid flushing by neutral to acidic waters, in which kaolinite is the dominant authigenic clay formed (see kaolinite discussion). Some of the Mg released from smectite in this fashion may ultimately be moved into other sub-surface zones where groundwater flushing is less rapid, and in which poorly leached, alkaline conditions prevail. In such zones, both neoformed chlorite and regenerated authigenic smectite may be precipitated. Since authigenic illite is also considered to form in such zones(see illite discussion), due to release of K from feldspar and mica breakdown, and from illite breakdown in the nearby strongly leached zones, authigenic mixed layer illite/smectite is probably a more common product.
- 2) In the same poorly leached alkaline subsurface zones described in (1) above, K derived from the breakdown of feldspars and micas may be adsorbed by pre-existing smectites or illite/smectites, causing them to authigenically regenerate as mixed layer illite/smectites of higher illite content than was previously the case.

Geographical and stratigraphical distribution of smectite in the Quartz Sandstone Sequence

Insufficient data is available to draw firm conclusions regarding the regional and stratigraphic distribution of smectite in the Quartz Sandstone Sequence. However, there are indications emerging of patterns; these are outlined below. Further sampling, utilising a more even and widespread sampling pattern with better stratigraphic control, would be very valuable in confirming and expanding upon the indicated patterns.

Regional distribution patterns

- 1) The above discussion of smectite genesis indicates that the regional distribution of smectite will be closely related to the regional distribution of the volcanic dust parent materials, since the presence of smectite appears to be related to the original presence of ferromagnesian-rich volcanic dust.

There may be some "smearing" of the original distribution patterns due to reworking and fluvial transport of the volcanic dust within the Early Triassic fluvial system. Fluvial transport of volcanic dust falling on upstream areas (towards the NW) into more southeasterly areas could partly account for the higher smectite concentration in SE Tasmania which is noted below. However it seems unlikely that such transport prior to final deposition could wholly account for dramatically higher smectite concentrations. Groundwater transport may also have caused some transport and redistribution of Mg ions during diagenesis, but this is likely to be a short-range effect causing little alteration to overall regional patterns of smectite distribution.

- 2) The dominant regional pattern is that the greatest concentration of smectite occurs in the southeastern part of the Tasmania Basin, in a broad band extending from Port Arthur northwest through the lower Derwent valley (see Fig. 7.10). This suggests that the main source of basic volcanic dust in the Early Triassic lay towards the southeast. The tendency of high-smectite sandstones to fall within a broad SE-NW trending band seems suggestive of broad plumes of volcanic dust being carried towards the NW by prevailing winds from the SE.

The lack of preserved volcanic clasts suggests that the source was relatively distant, so that only relatively fine-grained dust reached the currently exposed parts of the basin. However, the apparent gradient from high smectite concentrations in the southeast to much lesser concentrations elsewhere suggests that dust fallout was sufficiently rapid to produce a marked fallout gradient across the basin, which in turn suggests that the distance to the sources may be measured in the order of only a few hundred kilometres at most.

It is interesting that the majority of historic sandstone quarries used in the past are in the Hobart/SE Tasmania region, which explains the prevalence of smectite-related decay in so many historic Tasmanian buildings.

- 3) Considering the entire Tasmania Basin, a secondary regional pattern is expressed in the apparent tendency for smectite to be either present intermittently throughout the entire stratigraphic thickness of the dominantly sandstone interval of the Quartz Sandstone Sequence (eg, at Bothwell; see Appendix 11), or else to be entirely absent in numerous outcrops within a local region (eg, Ross; see Appendix 1).

This secondary pattern may simply reflect decreasing deposition of volcanic dust at greater distances from the volcanic source. Alternatively, it could be a reflection of prevailing wind directions in the Early Triassic, with plumes of volcanic dust being regularly blown across certain parts of the Tasmania Basin, and regularly missing other parts. A great deal of additional data will be necessary to distinguish between these two possibilities.

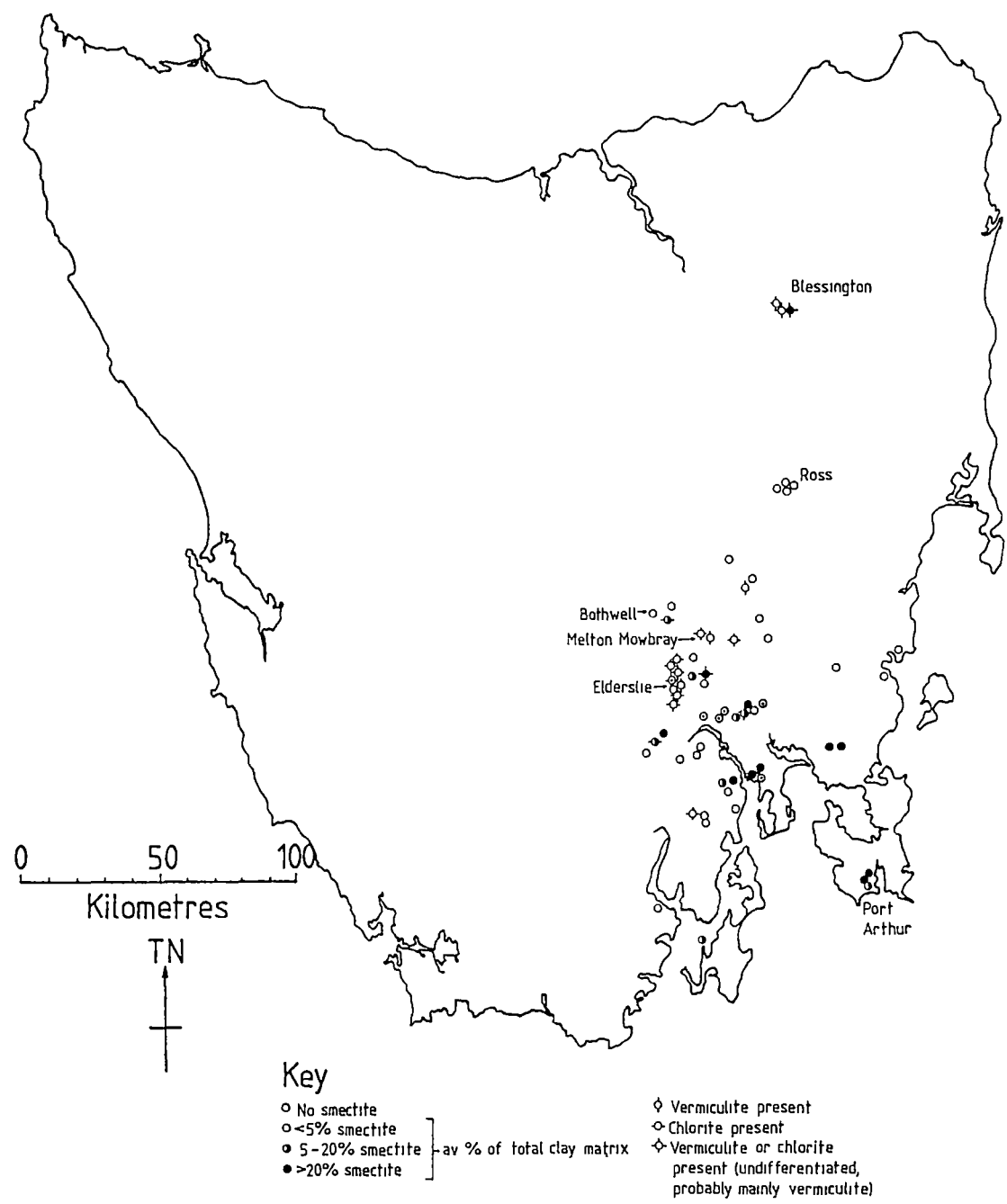


FIGURE 7.10 Geographic distribution of clay types in the Early Triassic Quartz Sandstone Sequence, Tasmania.
Data: Appendices 1, 8, & 9 - all quarries and sites for which clay types determined.
Appendix 11 - Bothwell drillhole, average smectite content indicated.

Stratigraphic distribution patterns

- 1) Those quarries and outcrop sites in the southeast of Tasmania which have the highest proportions of smectite (including the Port Arthur quarries, Kangaroo Point Green, Domain, Gordons Hill; see Appendix One) appear to be concentrated towards the base of the Quartz Sandstone Sequence. The Kangaroo Point Green Quarry occurs in the stratigraphically lower unit "Rls" in the Hobart area (Leaman 1972), while the Port Arthur Quarries are thought to be close to the base of the Sequence on regional mapping grounds (Cromer *et al.* 1976). However, the stratigraphic height of the Domain Quarries within the Sequence is unknown, and the Gordons Hill Quarries may be anomalous in that they are mapped with the unit "RIq" which, although not strictly a stratigraphic unit (see Chapter Three), commonly overlies "Rls".

In general, however, there is a distinct suggestion that the most intense period of Early Triassic vulcanism southeast of Tasmania occurred in the earliest part of the Early Triassic. This phase of vulcanism may therefore represent the waning phase of the volcanic episode towards the southeast which is thought to have affected the underlying Cygnet Coal Measures (Banks, *in* Burrett & Martin 1989,p.293).

More data from outcrops with good stratigraphical control will be necessary to test the existence of this suggested pattern. In particular, it will be necessary to sample horizons throughout the thickness of the Sequence in southeastern Tasmania, to determine whether the high smectite concentrations there are indeed confined to the lower horizons.

- 2) Clay analyses through the full stratigraphic thickness of the dominantly sandstone interval of the Quartz Sandstone Sequence drilled near Bothwell shows that smectite is intermittently present throughout. This indicates that some degree of vulcanism occurred throughout the Early Triassic, although probably at a lower intensity than during the Earliest Triassic.

The Bothwell drillhole is the only site at which smectite content has been measured in detail throughout the dominantly sandstone interval. The smectite occurs in horizons from less than two to over ten metres thick, interbedded with smectite free horizons two to fifteen metres thick (see Fig. 7.9 & Appendix 11).

This finding is important from the point of view of building sandstone exploration, since it suggests that even in regions dominated by smectite, it will be possible to find individual layers up to fifteen metres or so thick which will be free of smectite.

The data also raises interesting stratigraphic questions. It seems likely that individual smectite horizons represent individual pulses of volcanic activity. This suggests the possibility that a similar sequence of smectite-rich horizons might be found in the Quartz Sandstone Sequence throughout the Tasmania Basin. If so, the sequence of smectite-horizons would both record the history of waxing and waning of volcanic activity during the Early Triassic, and also provide a means of correlating widely separated sections of the Sequence.

However, the discussion of smectite origin and authigenesis above indicates that detailed smectite stratigraphy will not be amenable to such correlations, other than in a very broad way. This is because the detailed smectite stratigraphy has probably undergone significant modification as a result of both reworking of fluvial sediments during the period of deposition, and also through leaching and re-precipitation of

authigenic smectite during uplift and near-surface weathering. For instance, the major smectite-free horizon between 90 and 125 metres depth in the Bothwell drillhole is considered to reflect strong late-stage leaching of smectite rather than non-deposition of detrital smectite (see kaolinite discussion).

Overall, a pattern appears to be emerging which suggests the presence of an active volcanic centre somewhere to the southeast of the Tasmania Basin. This centre was probably most active during the Latest Permian, when it affected the Cygnet Coal Measures. The last major phase of basic volcanic eruptions occurred during the Earliest Triassic, after which the centre became more quiescent, although some vulcanism continued throughout the Early Triassic.

Volcanic activity again increased markedly in the Middle and Late Triassic (Collinson *et al.* 1987). This later vulcanism was probably closer, with basalts and tuffs being deposited in northeast Tasmania (Forsyth *in* Burrett & Martin 1989). The location of these extrusives and pyroclastics suggests that new sources towards the northeast had become active; the earlier southeastern source may have become completely inactive by that time.

(E) Vermiculite

Vermiculite was positively identified (by XRD) in three quarries in the Quartz Sandstone Sequence (Appendices 1 & 9). However it is considered to be relatively common in certain regions; undifferentiated "vermiculite or chlorite" in many outcrops sampled (Appendix 8) is considered likely to be vermiculite in most cases (see Section 7.6.3 B).

Of 17 Early Triassic quarries and outcrops listed in Appendices 1, 8 & 9 which contain vermiculite or probable vermiculite, 5 also contain smectite. No examples were found of sandstones containing both vermiculite and chlorite, although this is possible in some samples identified as containing undifferentiated vermiculite or chlorite.

Vermiculite and probable vermiculite is particularly common in a broad band extending from the Elderslie region through Melton Mowbray towards Oatlands, and also occurs in the Blessington area, near Launceston (see Section 7.6.3 B). In other areas, such as the Ross and Buckland-Orford regions, vermiculite appears to be rare or absent.

Vermiculite is also present in Permian sandstones at Nunamara quarry. The vermiculite occurs in association with authigenic chlorite (determined by SEM), but smectite is absent.

Vermiculite was not positively identified by SEM during this project. Although it can sometimes be identified morphologically (Sudo *et al.* 1981), it is commonly difficult to differentiate from aggregates of detrital or authigenic illite, for instance.

Vermiculites and probable vermiculites identified by XRD commonly gave moderately sharp peaks, but very sharp peaks are uncommon. The XRD evidence for detrital vs authigenic origin is therefore ambiguous. However, consideration of the possible sources of vermiculite suggests that its ultimate source was probably detrital.

The major source of vermiculites in sedimentary environments is as a weathering alteration product of biotite (Deer *et al.* 1966). In the absence of more direct evidence, it is tentatively assumed that the Early Triassic vermiculites were formed from a biotite precursor. In principle, biotite in the Early Triassic Tasmania basin could have been derived by either fluvial transport from the granitic sources to the northwest (probably in

Antarctica; Collinson *et al.* 1987), or by atmospheric transport as a component of volcanic dust derived from the postulated active volcanic sources to the southeast.

If the principle source of biotite was erosion of the granitic craton, the fluvial transportation processes would have spread it fairly evenly throughout the basin, so that the resultant vermiculite would be correspondingly widespread. However the vermiculite is distinctly concentrated in certain regions (see Section 7.6.3 B and Fig. 7.10). Moreover, the distribution of the vermiculite shows a relationship to that of the smectite (the possible significance of the relationship is discussed in the synthesis below). These observations suggest that the source of biotite is the same volcanic dust plumes from which pyroxenes for the production of smectite were derived.

The origin of the vermiculite is therefore considered to be related to that of smectite: fine-grained volcanic dust from active, probably basic, volcanic sources, containing both pyroxene/olivine/plagioclase particles (or glass of equivalent composition) and biotite was deposited in fine dispersions in the Tasmania Basin by atmospheric processes.

Fine crystalline biotite flakes have been recorded in recent volcanic ashfall deposits (eg, Wilson & Huang 1979, Summa & Verosub 1987). Biotite is characteristic of intermediate igneous rocks of calc-alkali affinities (Deer *et al.* 1966), and is common in rhyolitic pyroclastics (Summa & Verosub 1987). However, biotite also occurs in some basalts (Deer *et al.* 1966). The association of vermiculite with smectite in the Quartz Sandstone Sequence is suggestive of a basic volcanic origin; however, as with smectite, an origin by alteration of acid or intermediate volcanic deposits is not ruled out.

It is postulated that, whilst the pyroxenes altered to smectite under poorly leached, probably alkaline conditions, the biotites concurrently altered to vermiculite under similar conditions. Fluvial reworking probably occurred, with the vermiculite being ultimately deposited in the sands as detrital particles.

Whilst biotite can also weather to form smectite (Deer *et al.* 1966), it is possible that it may have been inhibited from doing so by its high K content. The excess K released by the biotites during their weathering may have contributed to illite formation. In strongly leached environments within the fluvial system, the biotite probably altered to kaolinite.

The volcanic biotite dust must have been of very fine grainsize, such that any which survived initial deposition was probably finally altered to vermiculite at an early stage of burial. This fine grainsize is necessary to account for the absence or rarity of recognisable unaltered volcanic dust particles in the Quartz Sandstone Sequence.

A. Spry (*pers. comm.* 1989) found that some of the vermiculite in the Elderslie Quarry (Source 26) occurs in rounded microscopic pellets having a "fibrous" structure and a suggestion of zoning. The fibrous and zoned structure is suggestive of pseudomorphing after biotite grains; the rounded pellets may be fine detrital biotites which survived fluvial transport and deposition, but then altered to vermiculite during early burial.

Bacon & Everard (1981) have described vermiculite in Late Triassic welded tuff deposits near Bicheno. They consider the vermiculite to have formed by syn-depositional alteration of volcanic biotite grains, although they consider the alteration mechanism to be hydrothermal reaction with the volcanic ash which in this case was deposited closer to the source as a hot mass. According to Deer *et al.* (1966), alteration of biotite to vermiculite may occur either by weathering or hydrothermal activity.

Subsequent to deposition, the Late Triassic vermiculites underwent further alteration as a result of low-temperature leaching, first to smectite, and then through further leaching to kaolinite (Bacon & Everard 1981).

It is unclear whether the Early Triassic vermiculites underwent diagenetic changes during deep burial. However, as discussed in Section (7.6.3 B), it is considered that with uplift and onset of oxidising conditions through exposure to oxygenated groundwaters under partially-leaching alkaline subsurface conditions, iron was leached from the vermiculite to form iron hydroxide (goethite or limonite). This gave the vermiculite-rich sandstones their characteristic brown bulk colour. As a result of Fe-depletion, it is likely that some of the Mg-rich vermiculites altered to smectites (which are Mg-rich, but generally have lower Fe content than vermiculite).

Further strong leaching in sub-surface aquifer zones or at outcrop surfaces would result in production of kaolinite from the vermiculite (as well as from any smectite or chlorite).

No processes by which authigenic vermiculite may have formed in the Quartz Sandstone Sequence during uplift and weathering are known, other than perhaps by minor alteration of large detrital biotites derived from granitic source rocks; the original volcanic biotite grains are thought to have been rather fine-grained, and would have completely altered to vermiculite during either deposition or early burial.

Whilst Kantorowicz (1984) has recorded the late stage alteration of chlorite to mixed layer chlorite/vermiculite during recent outcrop weathering, this process clearly has not operated in Tasmanian Triassic sandstones; on the contrary, while vermiculite probably occurs to considerable depth below outcrop surfaces in Early Triassic sandstones, chlorite-rich sandstones are themselves sometimes a near-surface phenomenon (see below - Bothwell Drillhole). In cases where chlorite can be shown to have altered during surface weathering, the effect is the production of goethite, probably with associated kaolinite formation (see Section 7.6.3 B).

The origin of vermiculite in the Permian Lower Freshwater Sequence sandstones at Nunamara quarry is problematical. Smectite does not occur in this deposit, and there is no evidence of contemporaneous vulcanism. However, the Nunamara quarry is close to the Devonian-Carboniferous granites of NE Tasmania, which are considered to have been an eroding highland region at the time of deposition (see Section 3.2.1, Fig. 3.1). The vermiculite may in this case have formed by alteration of detrital biotites derived from erosion of the nearby granites.

A test of this hypothesis would be to determine the distribution of vermiculite in Lower Freshwater Sequence sandstones throughout the Tasmania Basin. If the hypothesis is correct, vermiculite would only occur in sandstones which, like the Nunamara deposit, are close to granitic source regions. At greater distances, less biotite would have survived transport, and it would in any case be more dispersed.

(F) Chlorite

Chlorite was positively identified (by XRD and SEM) in only two quarries (Linden and Kangaroo Point Green) in the Quartz Sandstone Sequence (Appendices 1 & 9), and in the Bothwell drillhole (Appendix 11). It is considered to be relatively uncommon in the Early Triassic sandstones (see Section 7.6.3 B), although it is common in Middle to Late Triassic sandstones.

In all three Quartz Sandstone Sequence occurrences, chlorite occurs in association with smectite, but vermiculite does not appear to be present.

Chlorite also occurs in the Permian Nunamara Quarry sandstone. In this case it is not associated with smectite, but vermiculite is present.

Authigenic chlorite is readily identifiable using SEM (Wilson & Pittman 1977). Authigenic chlorite may be either pore-lining or pore-filling. Authigenic chlorite characteristically forms thin, delicate plates, sometimes roughly hexagonal in shape, attached to sand grains by their longest edge. Aggregates may form cellular honeycomb patterns, but are distinguishable from smectite honeycombs because individual chlorite plates can be distinguished, and they contact each other by a face to edge arrangement (rather than an edge-to-edge arrangement which would be similar to smectite). Authigenic chlorite plates may in some cases form discrete clusters of fan-shaped, rosette or "cabbage-head" form.

Using these SEM criteria, authigenic chlorite has been identified in all three of the Linden, Kangaroo Point Green and Nunamara sandstones (see Plates 7.21, 7.22 & Appendix 12). In all three cases, chlorite is only a minor constituent of the clay matrix (XRD determination), and no unequivocally detrital chlorite was identified. Although chlorite has been identified by XRD in detrital clay pellets from the Linden Quarry, these may easily have been altered by diagenesis or weathering.

In the Linden and Kangaroo Point Green sandstones, authigenic chlorite has been clearly observed growing on authigenic quartz overgrowths, indicating late stage authigenesis subsequent to quartz authigenesis (see Plates 7.21, 7.22).

In the Bothwell drillhole (see Fig 7.9), chlorite in the Quartz Sandstone Sequence was only identified by means of XRD, and commonly exceeded 10% of the clay matrix. However, apart from a lutite horizon deep in the hole, all the chlorite occurs within 50 metres of the surface; the 180 metres of Quartz Sandstone Sequence below this superficial zone is completely free of chlorite. This pattern of occurrence again suggests late-stage authigenesis in the final stages of uplift prior to actual surface outcrop weathering.

The comparative rarity of chlorite in the Quartz Sandstone Sequence, together with the evidence of a dominantly or entirely authigenic origin, suggests that the production of chlorite in Early Triassic sandstones is a minor diagenetic or weathering process.

Chlorite may occur in sedimentary rocks as an alteration product of ferromagnesian minerals, particularly biotites (Berry & Mason 1959, Deer *et al.* 1966, Huggett 1984, Morad 1984). Whilst such parent minerals are considered likely to have been available in the Early Triassic depositional basin (see discussions above), the rarity of chlorite and the abundance of smectite and vermiculite in the Quartz Sandstone Sequence indicates that, for reasons which are not clear, the chemistry of the depositional environment favoured production of the latter minerals rather than the alternative process of alteration to chlorite. Furthermore, the demonstrable occurrence of late-stage authigenic chlorite cannot be explained by the weathering of ferromagnesian minerals, since these are minor or absent

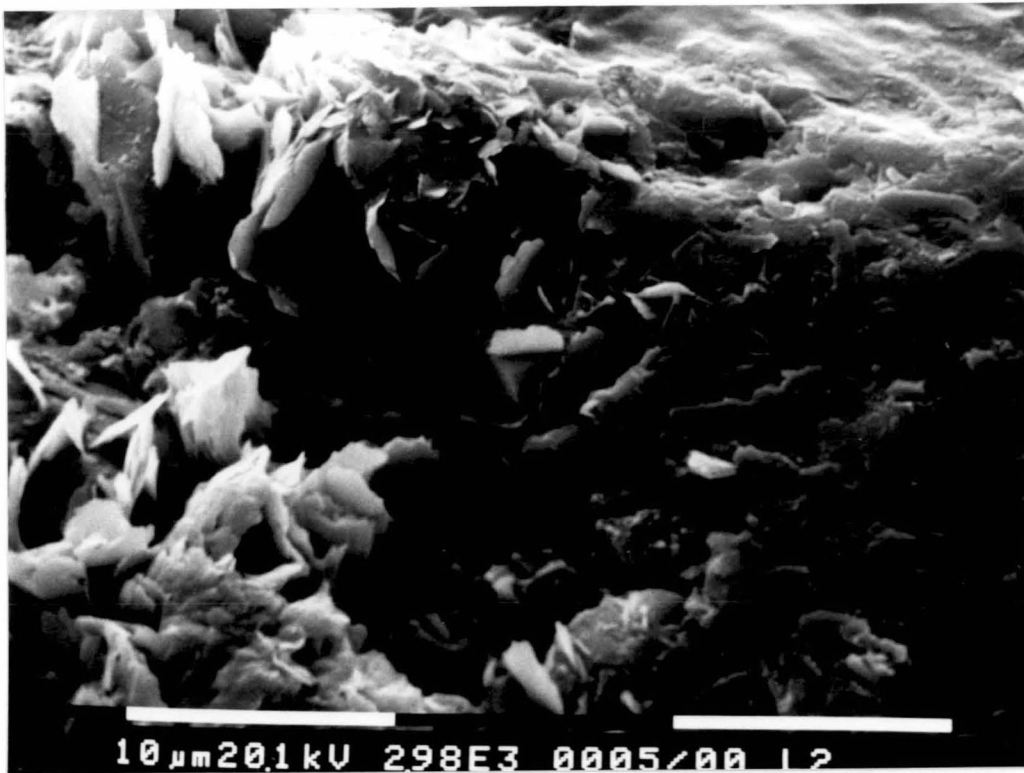


Plate 7.21 Authigenic chlorite flakes growing on authigenic quartz overgrowths in Early Triassic sandstone from Linden Quarry (Source 27, specimen L 2). One scale bar interval = 10 μ m (S.E.M.)

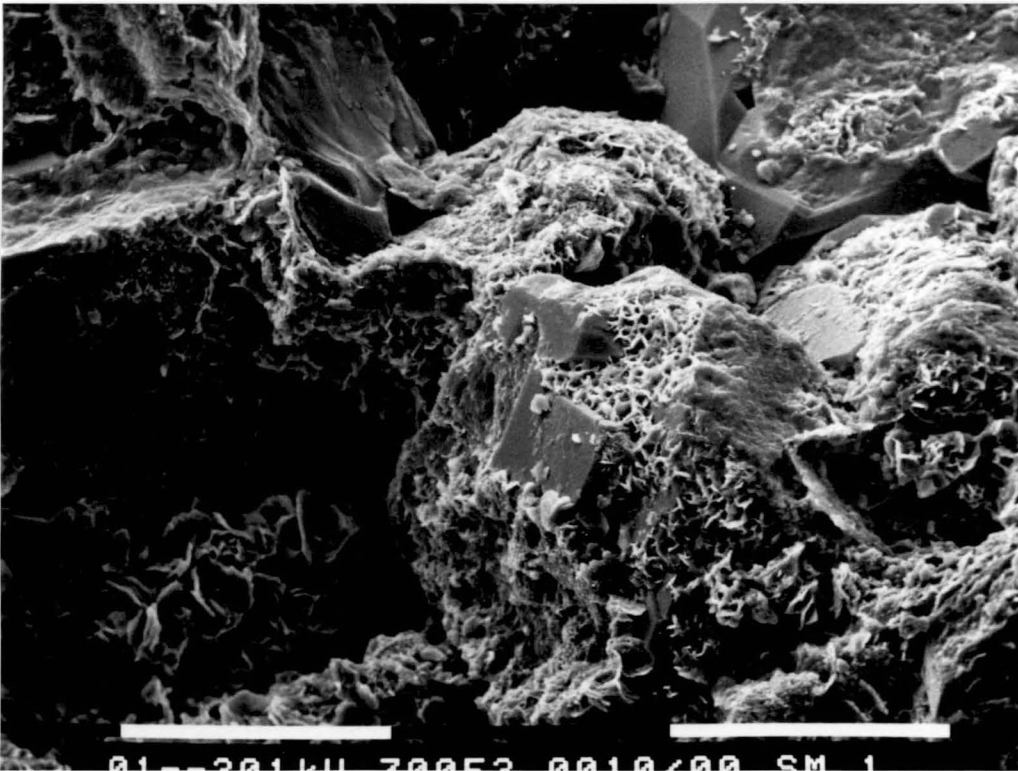


Plate 7.22 Authigenic chlorite (lower left) and smectite (centre) in Early Triassic sandstone from Kangaroo Point Green Sandstone Quarry (Source 4, specimen SM 1). Note two chlorite flakes growing on bottom of authigenic quartz face in centre. One scale bar interval = 0.1mm (S.E.M.)

in the sandstones today (having apparently been entirely altered to smectite and vermiculite at a much earlier stage).

It is likely that some authigenic chlorite formed during the deepest phases of burial of the Quartz Sandstone Sequence. In response to the elevated temperatures of deep burial, feldspars, kaolinite and smectite begin to break down (Folk 1974, Siever 1986); release of K (from K-feldspars and micas) through this process may lead to production of authigenic illite (See illite discussion, Folk 1974, Siever 1986).

At the same time, Mg released from partial smectite breakdown may combine with other ions released from the feldspar, kaolinite and smectite breakdown to form chlorite, which is the stable Mg clay under conditions of deep burial and low grade metamorphism (Deer *et al.* 1966, Folk 1974). Siever (1986) has documented the formation of chlorite in the Potsdam Sandstone (USA) under conditions of burial in excess of two kilometres. The Tasmanian Quartz Sandstone Sequence is likely to have reached comparable burial depths (see Everard *in* Turner & Calver 1987, p.144), so that minor diagenetic chloritisation of this nature is probable. Such chloritisation may be more prevalent in lower horizons which are likely to have been buried a little more deeply.

However, the only phase of chlorite authigenesis in the Quartz Sandstone Sequence which has been clearly demonstrated (by SEM evidence, see above) is the late stage authigenesis of chlorite subsequent to quartz overgrowth authigenesis. The distribution of chlorite in the Bothwell drillhole (see above) suggests that this chloritisation phase occurs in the last stages of uplift, immediately prior to exposure in surface outcrops.

Since vermiculite is not present at any depth in the Bothwell drillhole, it is unlikely that chlorite has formed by alteration of vermiculite, at least in this instance. The only apparent source of Mg in the drilled sandstones is smectite, which occurs throughout the hole, and is present in many of the chloritised samples. Smectite is also associated with other chlorites identified in the Early Triassic sandstones, at Linden and the Kangaroo Point Green Quarries.

Folk (1974) suggests that chlorite may form by weathering of smectite. It is considered (see smectite discussion) that smectite breaks down in strongly leached surface and near-surface zones subject to rapid flushing by neutral to acidic waters. Such a strongly leached, smectite-depleted, aquifer zone occurs in the Bothwell drillhole, below the chlorite zone. It is likely that some of the Mg (and Fe) released by breakdown of smectite in the strongly leached zone has moved into poorly leached near-surface zones, where authigenic chlorite has formed.

Interestingly, there is some evidence that both authigenic chlorite and authigenic smectite have been formed in the same sandstone horizons subsequent to quartz authigenesis. In specimen SM 1 (Kangaroo Point Green sandstone) both chlorite and smectite are observed growing on the same authigenic quartz crystals (see Plate 7.22). It is likely that chlorite forms during phases of late stage authigenesis when Fe is more abundant in the pore-waters, while smectite forms at times when less Fe is available. Significant variations in availability of Fe could occur during weathering for various reasons. For instance, an initial phase of chlorite formation would remove a significant amount of Fe from the system, with the result that smectite formation subsequently became favoured due to somewhat lower Fe concentrations in the porewaters.

This hypothesis cannot be applied to the occurrence of authigenic chlorite in the Permian Nunamara sandstone, however, since smectite is completely absent. A possible explanation in this case is that late stage chloritisation of relict detrital biotites, derived from nearby

Devonian-Carboniferous granites, may have occurred.

The fine grained volcanic biotites which are postulated to have been deposited in the Quartz Sandstone Sequence are considered to have been entirely altered to vermiculite by a relatively early stage of burial. However, relatively coarse detrital biotites of granitic origin in the Nunamara sandstone could have partially survived an initial phase of vermiculite formation, and so have been available for later chloritisation. If this is so, it is likely that some relict biotite would still be preserved in the sandstones today. Careful examination of the sandstone for relict biotites, and for chlorite pseudomorphs after biotite, would serve as a test of this hypothesis.

Synthesis: Clays in the Quartz Sandstone Sequence

Eggert (1983) distinguished three stages of authigenic clay formation in Tasmanian Triassic sandstones:

- 1) Early clays precipitated on detrital grain rims and as pore-lining cements (preceding quartz overgrowth formation).
- 2) Recrystallisation of detrital clay, compaction and recrystallisation of mudstone fragments to form intergranular pseudo-matrix clay cement, and extensive precipitation of quartz overgrowths was accompanied by further early clay precipitation on grain rims and lining pores.
- 3) Late authigenic clays precipitated as linings on remaining pore spaces, as pore-filling masses, and as replacements of feldspar grains.

In the light of the preceding discussions, the proposed origins of detrital and authigenic clays in Tasmanian sandstones can now be related to Eggert's three stages of clay authigenesis, summarised in terms of the stages in the history of the Early Triassic Quartz Sandstone Sequence (see also Figure 7.11):

1) Deposition

In addition to abundant detrital quartz, feldspars (including K-feldspars), micas and minor reworked illite were introduced into the depositional basin by fluvial transport from cratonic and unroofed orogenic sources to the west and northwest (western Tasmania and/or Antarctica). Simultaneously, fine grained ferromagnesian grains and glass particles, together with biotite dust, were introduced by aeolian transport from volcanic sources to the southeast.

In poorly leached parts of the depositional basin, the K-feldspars and micas were weathered to form illite, the ferromagnesian crystalline and glass particles altered to smectite, and the biotite dust altered to vermiculite. The smectite probably altered quickly to mixed layer illite/smectite by absorption of excess K from adjacent K-feldspars and biotites. Simultaneously, in strongly leached parts of the basin, all of the above-mentioned parent minerals altered to kaolinite.

After some fluvial reworking, all the clays so formed were finally buried as detrital clays, along with remaining unaltered grains of the parent minerals.

2) Early Burial

During the early phases of burial, while the sediment pile was still subject to infiltration by meteoric waters, alteration of parent minerals continued in a similar fashion to that prevailing during deposition. Authigenic kaolinite formed in strongly leached acidic aquifer zones, while authigenic illite, smectite and vermiculite production continued in poorly leached alkaline zones.

The more fine-grained, labile volcanic particles were probably completely altered to smectite and vermiculite during this phase, with the result that no further production of smectite or vermiculite from the original parent minerals was possible, and little or none of those parent volcanic particles are today preserved unaltered. A significant proportion of the larger detrital feldspars and micas remained partly or wholly unaltered.

This phase may correspond with Eggert's first phase of authigenic clay production.

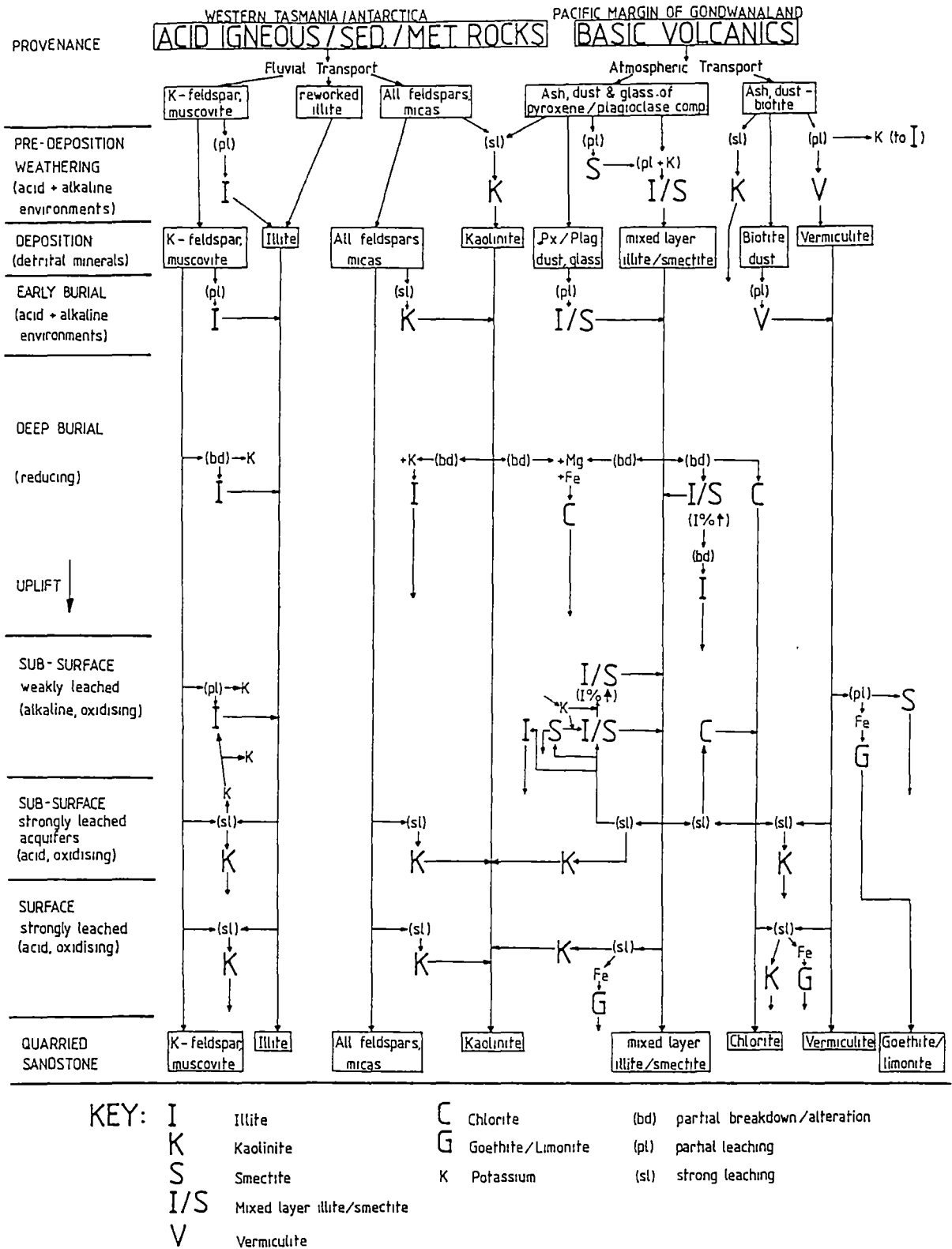


FIGURE 7.11 Schematic representation of postulated origins and authigenesis of clays in the Early Triassic Quartz Sandstone Sequence, Tasmania.

Note that the type of vulcanism and precursor minerals for smectite and vermiculite are simply those considered most probable or dominant; other vulcanism types and precursor minerals are possible (see text).

3) Deep Burial

With deep burial (probably >1.5km - *see* Everard *in* Turner & Calver 1987, p.144), the chemistry of the pore waters became progressively more reducing and were probably of close to neutral pH (Fairbridge, *in* Larsen & Chilingar 1967). The major phase of compaction and production of authigenic quartz cement took place at this stage (see Sections 7.9.1 J & K).

In the deepest stages of burial, increasing temperatures were accompanied by slow partial breakdown of kaolinite and smectite, and further slow alteration of feldspars (including K-feldspars) and micas. The materials released by this breakdown formed illite and chlorite, which are more stable under conditions of deep burial. The illite content of mixed layer illite/smectite clays probably increased somewhat. Since actual metamorphism did not occur, these diagenetic processes were probably relatively minor.

This phase corresponds to Eggerts second phase of authigenic clay production.

4) Uplift and near-surface alteration

With uplift, the sandstones once again became exposed to oxygenated meteoric groundwaters. This was probably the major phase of authigenic clay production.

In poorly leached alkaline sub-surface zones, alteration of K-feldspars and detrital micas once again accelerated somewhat, resulting in production of further authigenic illite, and addition of further illite interlayers to mixed layer illite/smectites. Partial leaching of Fe from vermiculite (and to some extent from smectite?) led to production of brown goethite/limonite cements.

Strong leaching of all clays, micas and feldspars in acidic subsurface aquifers produced authigenic kaolinite; K, Mg and Fe released by this strongly leaching probably contributed to further production of authigenic smectite, chlorite and illite in adjacent poorly leached zones.

Strong leaching of surface outcrops led to authigenic kaolinite production just below outcrop surfaces.

This phase corresponds to Eggerts third phase of authigenic clay production.

It is now possible to answer the first question posed in the introductory discussion of clays (Section 7.8.3), that is, to what extent can the occurrence of clay types in Early Triassic sandstone outcropping today be related to the occurrence of specific original detrital clays and other parent minerals? And to what extent is clay mineralogy controlled by diagenesis and weathering?

The answers, as proposed in this thesis, are summarised below:

- ILLITE:** Source: K-feldspars and micas introduced into basin by fluvial transport.
Occurrence: Ubiquitous and evenly distributed throughout basin by fluvial transport and reworking. Main control on present day abundance is degree of leaching (most importantly during uplift), therefore significant local variation but no regional patterns. Higher content likely in more feldspathic/micaceous horizons.
- SMECTITE:** Source: Volcanic ferromagnesian grains introduced by aeolian transport.
Occurrence: Restricted to volcanic plume pathways, more abundant closer to

source & lower in Early Triassic sequence. Secondary controls are intermittent phases of deposition and degree of leaching (most importantly during uplift), therefore significant local variation superimposed on gross regional and stratigraphic patterns.

VERMICULITE: Source: Volcanic biotite dust introduced by aeolian transport.
Occurrence: Restricted to volcanic plume pathways, possibly more abundant further from source than zone of maximum smectite concentration (see discussion below) and low in Early Triassic sequence (see Section 7.6.3 C). Probable secondary local variations due to leaching variations (most importantly during uplift).

KAOLINITE: Source: All clay source minerals and other clays.
Occurrence: Ubiquitous and evenly distributed through basin by fluvial transport and reworking. Main control on present day abundance is degree of leaching (most importantly during uplift), therefore significant local variation (abundant in sandstone bodies which have been major aquifers during uplift) but no regional patterns. Probably also more prevalent in the more feldspathic and micaceous horizons.

Although kaolinite is not particularly detrimental to sandstone durability in itself, the fact that the greatest production of authigenic kaolinite is related to intense fracturing and higher porosities (stronger leaching) means that sandstone having greater quantities of authigenic kaolinite is likely to be of lower quality and durability for building purposes.

CHLORITE: Source: Minor alteration product of smectite.
Occurrence: Restricted to smectite occurrence. Main secondary control is leaching during uplift, therefore significant local variations.

Variations in total clay content of sandstones

The second question posed in the introductory discussion of clays was, what net gains or losses of their total content of clays have sandstones experienced between deposition and exposure in quarriable outcrops? And, to what extent can the occurrence of high-clay or low clay sandstones be predicted?

As noted in Section (7.8.1), the relative proportions of detrital clay and sand grains in a fluvial sandstone at the time of deposition (that is, the sandstones textural maturity) depends upon the degree of clay winnowing produced by the hydrological regime at the deposition site. Detrital clay content will be proportional to sand grain size, sorting and bedding type, which are in turn related to stream power (and rate of change thereof in the case of "dumped" flood sediments).

Thus, if there were no alteration in quartz : clay ratios after deposition, total clay content in outcropping sandstones would be a function of grain size, sorting and bedding type. This is clearly not the case, as is indicated by the wide variation in total clay proportion between sandstones of similar bedding type, sand grain size and sorting. Authigenic growth (and dissolution) of clays, clay parent minerals and quartz, subsequent to deposition, appear to have significantly altered total clay contents.

As indicated by the preceding discussions, much clay diagenesis and weathering merely involves changes from one clay type to another. However, a number of mechanisms exist which may cause net gains or losses in the total clay content of a sandstone after deposition:

Net gains in total clay content:

- Alteration of detrital feldspars and micas to clay (illite and kaolinite).
- Alteration of detrital volcanic ferromagnesian minerals (pyroxene, olivine, biotite) to clay (smectite, vermiculite, kaolinite).

Net losses in total clay content:

- Alteration of clays to form authigenic micas (minor?).
- Loss of Fe from vermiculite, chlorite (and smectite?) to form ferruginous cements.
- Loss of silica from clays to form authigenic quartz overgrowths. Also, authigenesis of silica from other sources has increased the proportions of quartz relative to clay.

On the basis of the preceding discussions, the following patterns of net gain or loss of clay content are expected:

1) Net gain - alteration of detrital feldspar and mica

A small net gain in illite and kaolinite content can be expected as a result of breakdown of detrital (cratonic provenance) feldspars and micas. Such a gain would be greatest in the more feldspathic or micaceous sandstones (which tend to be more common towards the top of the Quartz Sandstone Sequence).

However, gains from this source are probably volumetrically relatively minor, since the preservation of many unaltered or only partially altered feldspars in outcropping Early Triassic sandstones indicates that feldspar alteration has been relatively slow and incomplete. While it is difficult to relate the proportion of surviving feldspars to the original (depositional) feldspar content, this evidence suggests that the degree of feldspar alteration has not been very great.

Nonetheless, Cainozoic weathering has resulted in notable destruction of labile grains (eg, feldspars) in some outcrops of the Sequence (Forsyth 1987). The degree of net clay gain from this source is correlatable with both feldspar content and degree of weathering experienced (ie, degree of leaching). The greatest clay gain from these sources has probably occurred in sub-surface aquifers and in surface outcrops, due to kaolinisation.

Interestingly, Nwajide & Hoque (1985) have demonstrated an inverse correlation between the proportion of (detrital plus diagenetic) clay matrix and the incidence of detrital feldspars in Cretaceous Nigerian feldspathic and subarkosic fluvial sandstones. They relate this to post-depositional alteration of the feldspars. If a similar relationship between (surviving) feldspars and illite + kaolinite content could be demonstrated in the Quartz Sandstone Sequence, it might provide a useful tool in attempting to estimate the net feldspar loss (and clay gain) which has occurred.

2) Net gain -alteration of detrital volcanic ferromagnesian minerals

It is possible that alteration of fine volcanic grains shortly after deposition may cause a notable increase in clay content, resulting in the sandstones ultimately having a significantly higher clay content (lower apparent textural maturity) than would be expected on the basis of their quartz sand grainsizes, sorting and bedding type.

Due to their probable fine grainsize and labile nature, a large proportion of the volcanic dust particles deposited on the Early Triassic fluvial basin probably decomposed to form smectite or vermiculite prior to final deposition. However, a

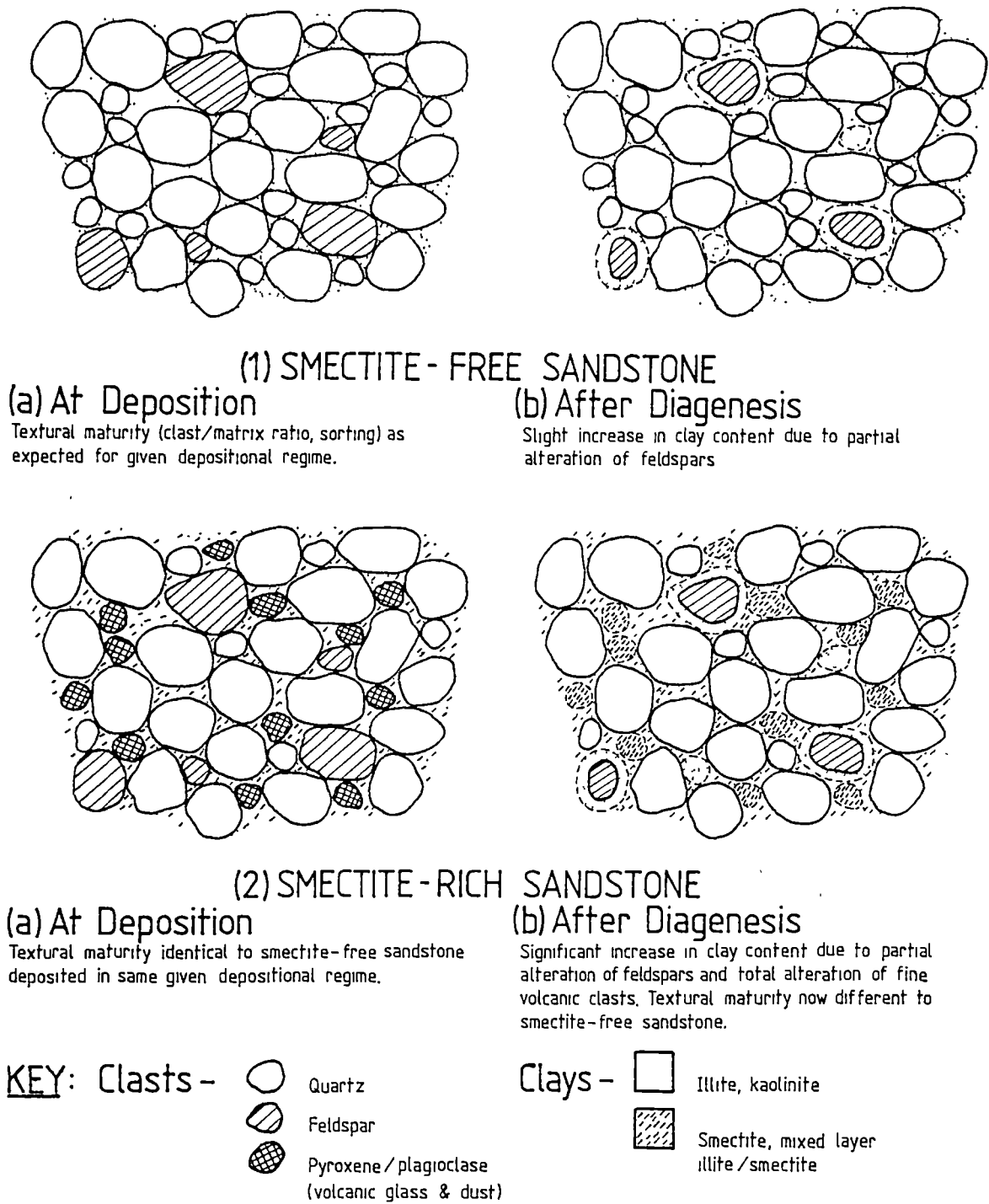


FIGURE 7.12 Mechanism of sandstone clay content increase subsequent to deposition. The effects of compaction, and quartz and ferruginous cement authigenesis, are not shown. Compare with actual smectite-rich sandstone (Plate 7.25) and fairly "clayey" but not smectite-rich sandstone (Plate 2.2).

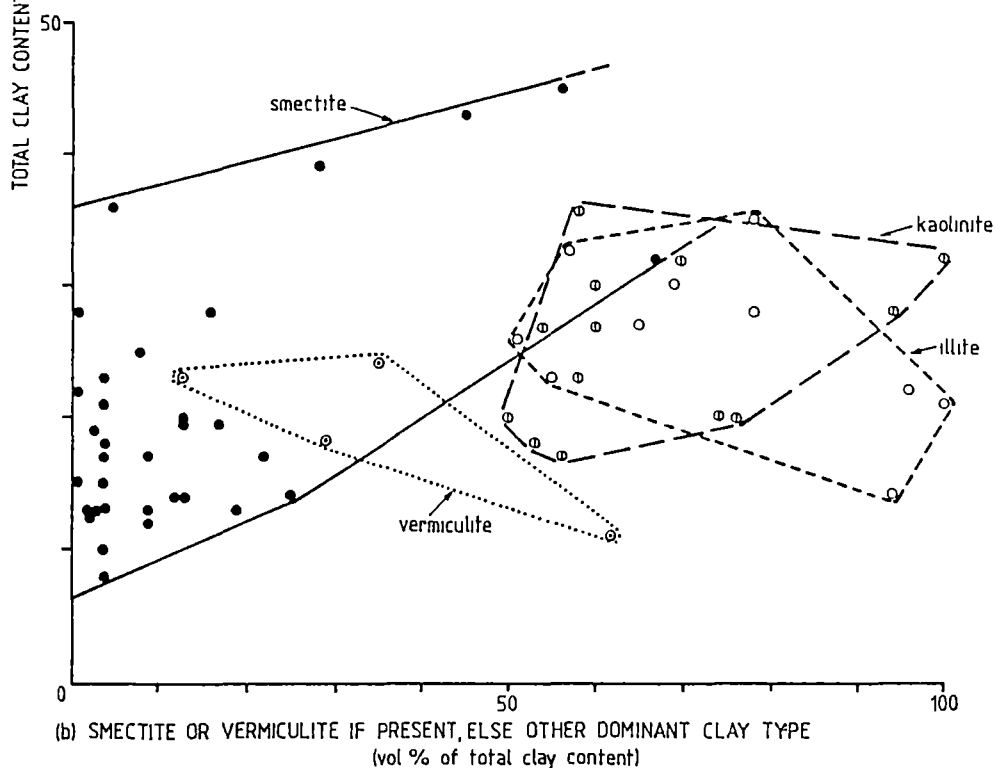
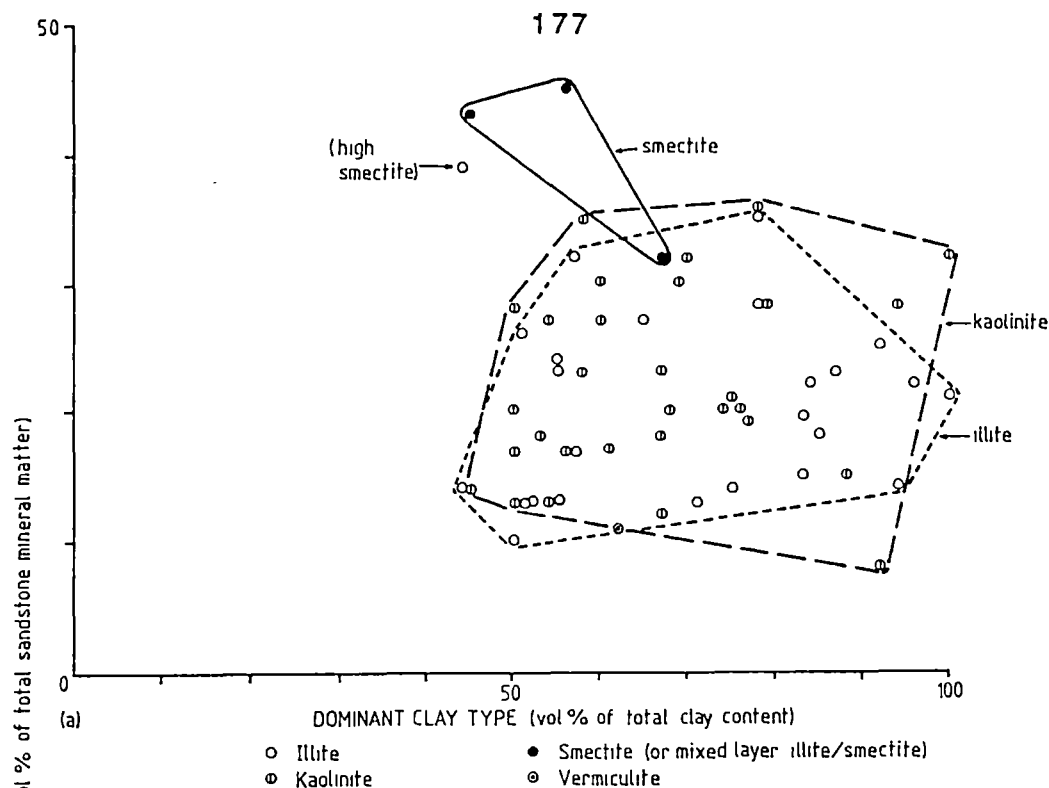


FIGURE 7.13 Early Triassic Quartz Sandstone Sequence: Relationships between total clay content and dominance of specific clay types.

Data: Appendix One - All Early Triassic specimens for which necessary information recorded.

- Includes fresh and weathered specimens, and colour-patterned specimens.
- Excludes salt-affected specimens.

proportion probably survived initial weathering and were deposited as clastic sand grains along with quartz and feldspar grains. At this stage, the sediment would have normal proportions of detrital clay and sand grains.

However, it was hypothesised above that the remaining fine-grained labile volcanic grains were probably completely altered to clay soon after burial; this would result in a significant increase in clay content. This process is illustrated in Fig. 7.12.

Data from quarries studied during this project appears to support this hypothesis. Figure 7.13 (a) compares the abundance of the dominant clay mineral in each sample with its total clay content (all clay types combined). For samples in which illite, kaolinite or vermiculite is dominant, total clay contents fall almost entirely within the range of 8 to 36% by volume of total rock mineral matter. No trend towards higher total clay content with increasing dominance of any of these clay minerals is evident.

However, the three specimens in which smectite was dominant form a field of distinctly higher total clay content. Although the data on specimens with very high smectite content is limited, this does suggest that higher total clay contents are characteristic of high-smectite stones.

In Figure 7.13 (b), data from the same specimens is organised differently: for specimens containing any smectite at all, the smectite proportion of the clays present is compared to the total clay content of the stone. There appears to be a clear trend evident: higher proportions of smectite in the clay matrix tend to be related to higher overall clay content in the stone. Where less than 25% of the total clay content comprises smectite, total clay contents are comparable to sandstones which are free of smectite. However, greater proportions of smectite in the clay matrix are related to total clay contents in excess of those in non-smectite stones.

Thus, there is a clear suggestion that high-smectite sandstones will have low durabilities not only because of their swelling properties, but also because they will tend to have higher overall clay contents (and thus a weaker intergranular texture). The cause of these higher clay contents is considered to be that outlined above, and illustrated in Fig. 7.12. However, the relatively sparse nature of the data on high-smectite sandstones is such that it would be desirable to collect additional data to give better support to this idea.

In contrast to the effects of smectite, it is notable that Fig. 7.13 (b) does not indicate a similar increase in total clay content with increasing proportions of vermiculite (also derived from fine volcanic dust). There are probably two reasons for this:

- The fine volcanic biotite dust which is considered to be the parent mineral for the vermiculite would have decomposed during initial weathering more quickly than the possibly coarser, and certainly more resistant pyroxene/plagioclase grains which are thought to be the main smectite precursor. Thus, a larger proportion of biotite dust was probably converted to vermiculite prior to final deposition, so that only a small amount of the biotite was buried to be finally altered to clay, and so alter the apparent textural maturity of the sand at a later stage.
- In addition, a significant volume of vermiculite was probably later lost during uplift, when Fe was released to form ferruginous cements (see below).

3) Net loss - alteration of clays to mica

It is difficult to assess the amount of clay matrix which may have been depleted to form authigenic micas during deep burial. However, the low micas content of most Early Triassic sandstones suggests that this would be a minor effect. The micas would probably form by alteration of K-rich Illite.

4) Net loss - Fe depletion of clays

It is considered that Fe-rich clays may break down during uplift and oxidation, releasing Fe to form ferruginous cements. This process is considered to be a major one in vermiculites, and may affect chlorite and smectite to a smaller extent (see Fig. 7.11 and Section 7.6.3 B).

The quantities of clay lost through Fe-depletion may be significant. Vermiculite-rich sandstone at Elderslie Quarry has a ferruginous cement typically comprising 3 to 5% of the total stone (see Section 7.11.1, Table 7.2). The iron in the cement is probably largely derived from vermiculite breakdown. Although at least some of the materials from the vermiculite breakdown probably went to form other clays such as smectite, this quantity of ferruginous cement suggests a moderate net clay loss.

5) Net loss - silica depletion of clays

Silica authigenesis is discussed in Section (7.9.1) below. The breakdown of detrital kaolinite and smectite during deep burial or surface weathering releases silica which may precipitate as quartz, thereby reducing the total volume of any authigenic clays formed from the other products of the detrital clay dissolution.

In summary, all Early Triassic sandstones have experienced a modest increase in clay content since deposition due to alteration of feldspar and mica to illite and kaolinite. This effect would be greatest in the most feldspathic and micaceous sandstones. Where smectite is present a further increase in total clay content can be expected, becoming more significant with greater proportions of smectite in the clay matrix.

On the other hand, some loss of clay content during burial and uplift can be expected in all sandstones due to alteration to mica (probably insignificant) and transfer of silica from clays to authigenic quartz. Loss of vermiculite clay due to Fe-depletion can result in vermiculite-rich sandstones losing a modest proportion of their total clay content.

With diagenetic processes active which cause both clay loss and gain, it is in most cases unclear whether the net result is an overall gain or loss in clay content subsequent to deposition (although a modest overall gain is suspected). No attempt was made to answer this problem during the present work.

At present, the best guideline to net clay gain/loss is that sandstones whose clay matrix includes in excess of 25% smectite (or mixed layer illite/smectite) appear to have experienced a significant gain in total clay content since deposition, and so tend to have the highest total clay contents of any sandstones studied.

The significance of vermiculite and smectite distribution patterns

Both the smectite and vermiculite in the Quartz Sandstone Sequence are considered to have formed by alteration of volcanic grains, glass and dust deposited from volcanic dust plumes carried over southeastern Tasmania from a volcanic source further to the southeast. Both the smectite and the vermiculite (see Section 7.6.3 C) are most common in the lowest parts of the Sequence, although at least the smectite occurs intermittently throughout the Sequence.

The occurrence of both clay types in a broad linear band in southeastern Tasmania, with sandstones free of smectite and vermiculite occurring to the northeast of this band, is suggestive of discrete plumes of volcanic dust controlled by prevailing winds blowing in a fairly constant direction throughout the period of vulcanism (see Fig. 7.14).

A further (separate?) region of smectite and vermiculite occurrence near Blessington could represent a different plume from a different source.

The first significant conclusion to be drawn from these patterns is that sandstones free of smectite and vermiculite are most likely to occur inbetween these two main areas affected by the volcanic plumes. A great deal of additional data is necessary to properly map the distribution of the smectite/vermiculite sandstones. Apart from being useful in building sandstone exploration, the present work suggests that such mapping will yield valuable information on the location of Early Triassic volcanic centres, as well as possibly yielding information on large-scale weather patterns (ie, prevailing wind directions) at the time of deposition.

Examination of Fig. 7.11 suggests a further pattern which may be of significance: considering only the broad NW - SE band of smectite/vermiculite occurrence in southeastern Tasmania, it is apparent that smectite is dominant towards the SE part of the band (probably closer to the source), while vermiculite is more dominant towards the NW part.

As discussed above, the main parent material for the smectite is considered to have been volcanic grains and glass particles of ferromagnesian composition, whilst the vermiculite parent material is thought to have been biotite dust.

Since volcanic biotite dust takes the form of flat platy grains (eg, see Wilson & Huang 1979, Fig. 1 E), it might be considered that biotite dust would fall slower, and so remain in the atmosphere longer, than more equant or irregularly shaped ferromagnesian crystal fragments or glass particles, and so be deposited further from the source than the latter. This would explain the observed vermiculite/smectite distribution.

However, Wilson & Huang (1979) have shown that flattened particles actually settle out of the atmosphere faster than more equant particles of the same mean diameter. This is because the tumbling motion of particles in the atmosphere results in flattened particles having a lower average cross-sectional area presented normal to the direction of motion than do equant grains.

Aside from the shape factor, however, it can be shown that the settling velocity of volcanic particles in the atmosphere does decrease with decreasing particle size and density (Wilson & Huang 1979).

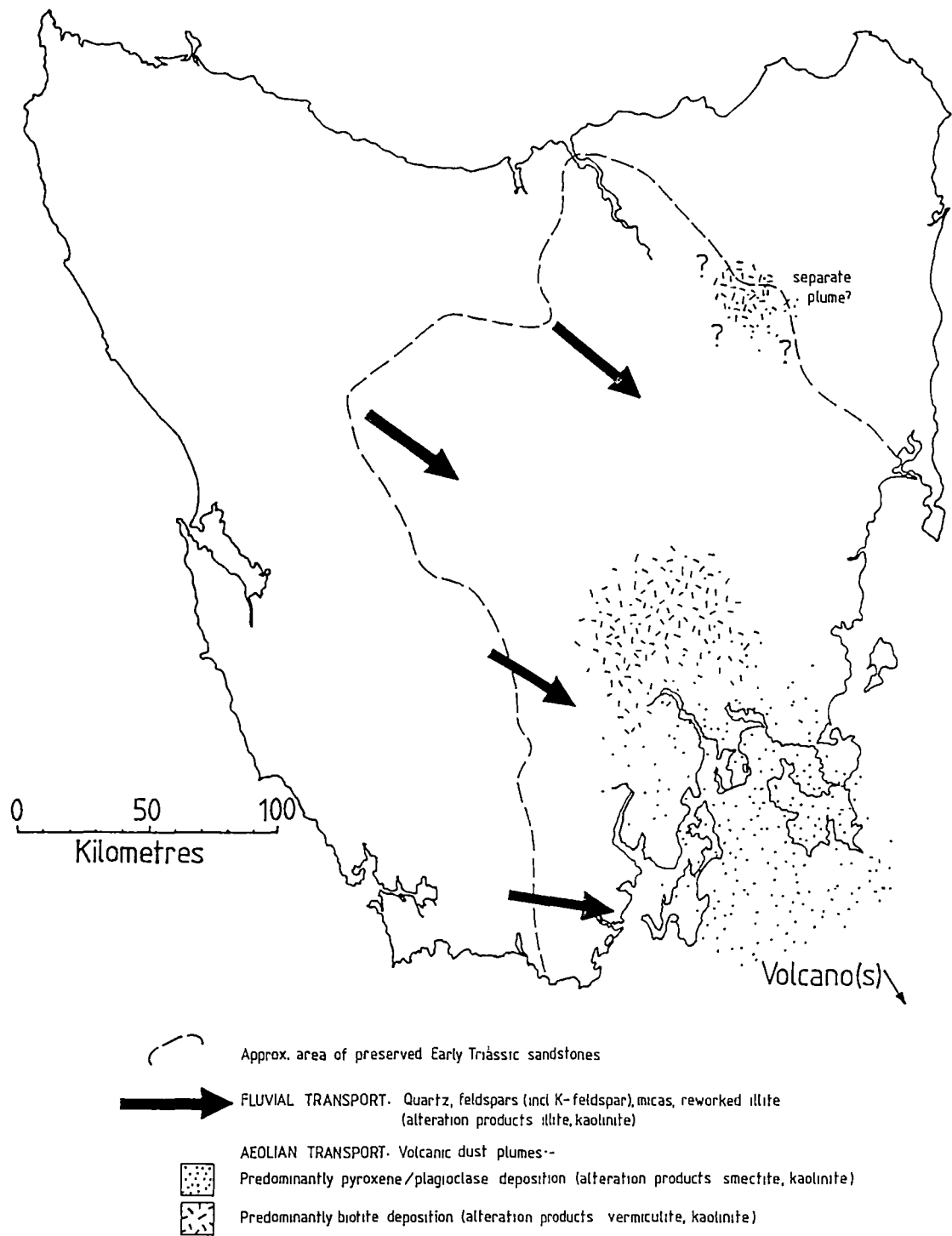


FIGURE 7.14 The provenance of minerals deposited in the Early Triassic Tasmania Basin (Quartz Sandstone Sequence).

In the light of these considerations, the occurrence of smectite and vermiculite in different parts of the same broad band can be explained by hypothesising the occurrence of two different dust or ash fractions in the volcanic dust plume, namely:

- 1) Very fine grained dust particles consisting predominantly of biotite, which settled slower and so travelled further from the source prior to deposition, and:
- 2) Somewhat coarser (albeit still fine-grained) dust, ash and glass particles of predominantly pyroxene, olivine and plagioclase composition, which could not remain aloft as long, and were deposited closer to the source.

Crystalline biotite, with its well-developed cleavage, would tend to fragment more easily during eruption than would glass or other crystalline materials, and so would form a distinctly finer-grained fraction of the volcanic dust cloud. Rose *et al.* (1980) have hypothesised a similar process for dust fractions sampled from modern Central American volcanic dust clouds. They found that well-cleaved crystalline fragments form a distinctly finer fraction than do the amorphous volcanic glass particles.

Undoubtedly additional fractions were present in the Early Triassic volcanic plumes, ranging from coarser ash deposited closer to the source, to very fine dust which (by comparison with modern volcanoes) could potentially achieve a nearly global distribution.

Figure 7.14 illustrates this hypothesis. The two dust fractions would partially overlap and intermix in their depositional patterns, producing the observed mixing of smectite and vermiculite at some sites. However, the broad pattern seems sufficiently distinct to be used as a guide to the occurrence of brown vermiculite sandstones with minimal smectite, and sandstones free of either smectite or vermiculite.

More detailed sampling and mapping is required to either confirm or disprove the reality of these distribution patterns. In so doing, the usefulness of the patterns as a guide to exploration will be greatly enhanced.

A direct test of the volcanic dust plume hypothesis

The hypothesis presented above, that smectite and vermiculite in the Quartz Sandstone Sequence are derived from alteration of volcanic dust, is based essentially upon indirect evidence and consideration of the most probable means by which these clays may have formed.

Direct evidence of this hypothesis would take the form of the presence of actual relict volcanic particles, or identifiable pseudomorphs thereof, in the Quartz Sandstone Sequence. It has been argued that these will be rare due to the necessity for the volcanic dust deposited to have been very fine grained, and for it to therefore have altered entirely to clay at an early stage.

However, the hypothesis suggests that the volcanic sources were situated to the southeast of Tasmania, and that, while fairly distant, they were nevertheless close enough for a notable fractionation in the type of particles falling out to be discernable across the Tasmania Basin. This implies that the coarsest volcanic particles would have been deposited in the extreme southeastern part of the basin (Port Arthur/Tasman Peninsula area). Such coarser particles would be the most likely to have partially survived diagenesis.

It is therefore suggested that a careful search for relict volcanic particles be conducted on sandstones from the Tasman Peninsula area. Discovery of such particles would serve to not

only support the hypothesis, but also to give more direct evidence as to the type of vulcanism (basic or otherwise).

7.8.4 Ferruginous minerals (cements)

The most common ferruginous minerals in the Quartz Sandstone Sequence are goethite or limonite stains or cements which may make a small contribution to sandstone strength (see Plate 7.26) but, more importantly, are the major determinant of sandstone colouration. The origin of these minerals is discussed in Section (7.6); briefly, they are thought to be primarily related to the alteration of vermiculite, chlorite, and possibly smectite clays in the sandstones, and to the proximity of Jurassic dolerite intrusions.

Other iron minerals which may occur in the Quartz Sandstone Sequence include pyrite, marcasite, siderite and magnetite (Threader 1982, Forsyth 1987). These are very minor components which will rarely pose a problem in regard to use of the stone for building purposes.

7.8.5 Other minerals

Mica

Mica generally comprises less than 1% of sandstones in the Quartz Sandstone Sequence, although in the Hobart and Brighton Quadrangles it is more common towards the top of the Sequence (Leaman 1976, 1977).

Mica may occur concentrated on bed planes and cross-bed laminae (in which case it is detrimental to stone quality for building purposes, as easy splitting results), or as minor dispersed grains (in which case it has little effect on stone durability). Microscopic examination commonly reveals the mica flakes to be bent or broken during compaction, indicating a detrital origin. No evidence of authigenic mica was noted during this project, although this possibility is not ruled out.

Eggert (1983) found that biotite is more common than muscovite in Triassic quartz sandstones. The detrital mica is probably derived from granitic and metamorphic terranes in western Tasmania or Antarctica (Collinson *et al.* 1987).

Graphite

Graphite has been noted in the Quartz Sandstone Sequence in a few outcrops. At Elderslie quarry it occurs in association with mica on cross-bed laminae. It is detrimental to sandstone durability since it facilitates easy splitting along bed planes.

Graphite is derived from alteration of organic materials. No patterns were detected in its occurrence.

7.9 STRENGTH AND DIMENSIONAL STABILITY

Whilst nearly all sandstones have sufficient compressive strength to withstand normal compressive loadings in buildings, tensile strength is a major determinant of sandstone durability, in that it controls the susceptibility of intergranular bonds to break down in response to decay processes such as salt attack and clay expansion. The compressive and tensile strength of sandstones are determined by the same fundamental properties of the stone, and have been shown to have a proportional relationship (eg, see Broch & Franklin 1972, Read *et al.* 1980).

Sandstone strength is required to be as high as possible for maximum durability, although excessive strength (as in some metamorphic quartzites) may make stone too hard to be worked economically. Recommended minimum strengths for building sandstones are given in Appendix Four.

Dimensional stability is largely related to the same sandstone properties which control sandstone strength, and is discussed in Section (7.9.2) below.

7.9.1 Factors determining strength of sandstone

Sandstone strength is considered to be a function of the following sandstone properties:

- Grainsize
- Sorting and homogeneity
- Grainshape (roundness & sphericity)
- Grain orientation (fabric)
- Grain packing, interpenetration and interlocking
- Porosity
- Micro-fracturing
- Mineralogy: Proportions of quartz, clay, ferruginous minerals, etc.
- Presence of laminae (clay, mica, graphite, oriented quartz grains)
- Intergranular bonds:
 - quartz grain welding
 - authigenic quartz cement
 - ferruginous cement
 - clay bonds

Laminae of clay, mica, graphite or oriented quartz grains are essentially a macroscopic feature which cause easy splitting of stone along bedding. Micro-fracturing is a secondary feature which causes strength loss by disrupting sandstone textures.

All the other properties listed, however, are fundamental properties whose main importance in this context is that they contribute to the determination of a sandstone's "Intergranular Texture" (see Section 2.3.4). Intergranular texture can be considered to be the relative proportions and types of intergranular bonds (quartz, clay, ferruginous) holding the sand grains together. Carbonate cement bonds, whilst common in some sandstones, are rare or absent in the Early Triassic and Permian sandstones which are used for building purposes in Tasmania (see Chapter Three).

Spry (1976, 1983,p.30) has shown that, in general, the strength of sandstone as a whole depends upon the strength of the intergranular bonds. Quantitative investigations of relationships between intergranular texture and strength have not been undertaken in the present project, due to a lack of quantitative intergranular texture data, but such investigations of Tasmanian sandstones are recommended.

Thus, sandstone strength is essentially proportional to intergranular texture.

Variations in stone strength may occur due to defects, including micro-fractures, and in response to varying chemical and physical conditions imposed upon the stone (eg, temperature, degree of wetting).

Due to its fundamentally bedded nature virtually all sandstones show some strength anisotropy, being weakest parallel to bedding. This is true even of ostensibly massive sandstone, free of any obvious laminations. The strength anisotropy is considered likely to be due to a degree of sub-parallel orientation of more elongate quartz grains, to a tendency towards an aligned fabric in microscopic clay matrix masses, and to the effect of scattered mica flakes oriented parallel to bedding.

The following discussions consider the origin, and contribution to determining intergranular texture and strength, of each of the fundamental sandstone properties listed above:

(A) Grainsize

Grainsize (see Section 2.3.1) influences stone strength, in that stone strength increases with decreasing grainsize (Brace 1961, Winkler 1973, Spry 1976, Singh 1988). This is related to the ease of propagation of fractures and to the larger grain boundary surface area per unit volume which is available for quartz-quartz bonding in finer-grained stones (Spry 1976).

Dreyer (1972) studied the relationship between strength and grainsize in rock salt (halite). Although not directly applicable to sandstone, similar principles will probably apply to sandstones having a significant proportion of crystalline quartz-quartz bonds.

Dreyer found that at very coarse grainsizes (<15 grains/cm²) rock strength increases rapidly with decreasing grainsize. Between 15 and 60 grains/cm² there is a moderate increase in strength with decreasing grainsize, and then at grainsizes finer than 60 grains/cm² there is little change in strength with decreasing grainsize.

As grainsize becomes very coarse (tending towards 1 grain/cm²), rock strength approaches simple crystal strengths. Thus, aggregates of a mineral tend to be stronger than a single crystal of the mineral.

Whether grainsize variation in the range of fine-medium grained sandstones will cause significant strength variations has not been determined in the present project. However, it is suspected that in this grainsize range, the effects of varying proportions of quartz versus clay bonds over-ride any simple grainsize effects.

Indeed, in Tasmanian Early Triassic sandstones, finer grainsizes tend to be related to higher clay contents (see Section 7.8.1), and thus to lower strengths.

Regional and stratigraphic variations in grainsize within the Quartz Sandstone Sequence are dealt with in Chapter Three, and in Section (7.5).

(B) Sorting and homogeneity

Grain sorting (Section 2.3.2, Appendix A 3.2.1) is a measure of the standard deviation of grainsizes from the average diameter. Homogeneity (Dreyer 1972) is a related parameter which measures the degree of variance in grainsize.

Dreyer (1972) found that the strength of rock salt increases slightly with increasing homogeneity. This finding may have some relevance to quartzites having a high proportion of

crystalline intergranular bonds (like rock salt).

However, building sandstones have a high proportion of clay bonds in addition to crystalline quartz bonds. Poorer sorting in sandstones is generally related to a higher clay content, with the poorest sorted sandstones being high-clay greywackes (eg, Sarah Island greywackes, Source 20). It is therefore likely that poorer sorting in Tasmanian building sandstones is related to lower strengths due to an increasing proportion of weak intergranular quartz-clay bonds.

No attempt was made to determine the distribution and controls on sorting variations in the Quartz Sandstone Sequence specimens studied in this work; however practically all specimens were moderately to well sorted (0.35 to 0.50 σ standard deviation), and it seems unlikely that sorting, in itself, would be a significant cause of strength variation within this range.

(C) Grainshape (roundness and sphericity) and Grain orientation (fabric)

Grainshape and orientation (see Section 2.3.3) may have a significant effect on the development of sandstone strength during deposition, early burial and compaction.

Deposition of low-sphericity, elongate particles under fluvial conditions gives rise to an aligned fabric, wherein the long axes of quartz clasts lie sub-parallel to each other, and which causes a significant strength anisotropy. A moderate microscopic quartz clast alignment of this nature has been observed in many of the more well-bedded sandstones studied in this project; the resulting strength anisotropy of well-bedded stone is a major reason for massively bedded stone being preferred for most dimension stone applications.

In regard to roundness, Chilingarian & Wolf (1975,v.1, p.299) note that rougher particles may interlock better, giving greater strength than smooth particles. However, the roundness of Tasmanian Early Triassic sandstones has been greatly altered by the development of quartz overgrowths during diagenesis. Although "dust rings" on many clasts indicate original well-rounded detrital grainshapes, the extensive development of authigenic quartz has given most grains a subangular to angular shape.

It is considered that the development of authigenic quartz cement greatly dominates the importance of original grainshapes in determining the strength of Tasmanian building sandstones.

(D) Grain packing, interlocking and interpenetration

Quartz grains in a clay and/or silt matrix may be packed in either a closed or open framework texture. An open framework texture, in which grains "float" in the clay matrix with few grain-to-grain contacts, is characteristic of greywackes, and is very weak.

Tasmanian building sandstones have a closed framework, in which most quartz grains are in direct contact with other grains; this produces higher strength. Within the class of closed framework sandstones, greater strength is largely dependant on greater proportions of strong grain-grain contacts as opposed to weaker grain-clay contacts. This important feature is the basis of intergranular texture, and is dependant on the various criteria discussed below.

During deposition and compaction, the tightness of grain packing determines the proportion of grain-grain contacts. In an ideal sandstone consisting of perfectly spherical quartz grains of constant diameter, it has been shown that six different systematic ways of packing the spheres are possible (Blatt *et al.* 1972,p.71). Cubic packing is the loosest, and

rhombohedral the tightest. However, in real sandstones, with variable grain diameters and shapes, and varying quantities of clay matrix interfering with the grain packing, such ideal packing arrangements are not achieved. More or less random packing arrangements are common in nature (Blatt *Ibid.*), and prediction of their average geometrical properties is difficult.

As noted above, a greater degree of grain interlocking may give rise to higher strength (Dreyer 1972). Increasing roughness (angularity) of grains gives rise to better interlocking (Chilingarian & Wolf 1975). However, in Tasmanian sandstones, the growth of authigenic quartz cements over-rides the effect of interlocking of the detrital grains (and indeed, creates a form of authigenic interlocking).

Interpenetration of quartz grains during compaction and pressure solution is common in Tasmanian sandstones, and produces strong welded grain contacts. These are discussed below.

(E) Porosity

Whitely (1983,p.91) considers strength to be crudely related to porosity in that, with increasing porosity, strength will be reduced because there is less solid mass per unit volume to bear stress, and the stress is localised at fewer grain contacts. Chilingarian & Wolf (1975, v.1, p.299, 319) also consider the strength of porous materials such as sandstone to be significantly controlled by the properties of the pores.

The porosity (or water absorption) of Tasmanian sandstones is considered to be produced not only by open interstitial pore-spaces or micro-fractures, but also by absorption of water in the clay matrix (see Section 7.10). However, since greater proportions of all three stone characteristics lead to a lowered proportion of strong quartz-quartz grain bonds, increasing porosity may still be expected to produce decreasing strength.

Figure (7.15) overleaf compares the strength and porosity of all sandstone specimens tested during this project. Inspection of the figure shows that a definite trend does exist towards higher strengths with lower porosities. The trend is, however, rather vague.

The writer considers this vagueness to be caused by the fact that certain stone properties which have a significant influence on strength may have a lesser influence on porosity (or vice versa), leading to a relatively low correlation of one variable with the other. Such properties include the relative proportions of clay which occur as interstitial fillings or intergranular films. For a given total volume of clay, porosity is probably little affected by the particular mode of clay occurrence; however strength is highly dependant on whether the clay occurs interstitially or as intergranular layers and films.

Increasing porosity is also considered to be a factor in increasing the degree of strength loss due to wetting (see Section 2.5.3). This is because increasing porosity is partly related to a higher proportion of water-absorbent clay bonds (which lose strength upon wetting), and also because increasing porosity allows better access of water to those same clay bonds.

Since wet/dry strength ratios have not been measured for most specimens in the course of this project, it is not presently possible to determine the degree of correlation which exists between porosity and loss of strength with wetting.

The controls on variation of porosity in Tasmanian sandstones are discussed in greater detail in section (7.10). However, since the correlation of strength with porosity *per se* is only a vague one, the writer considers it to be more valuable to consider porosity as a gross

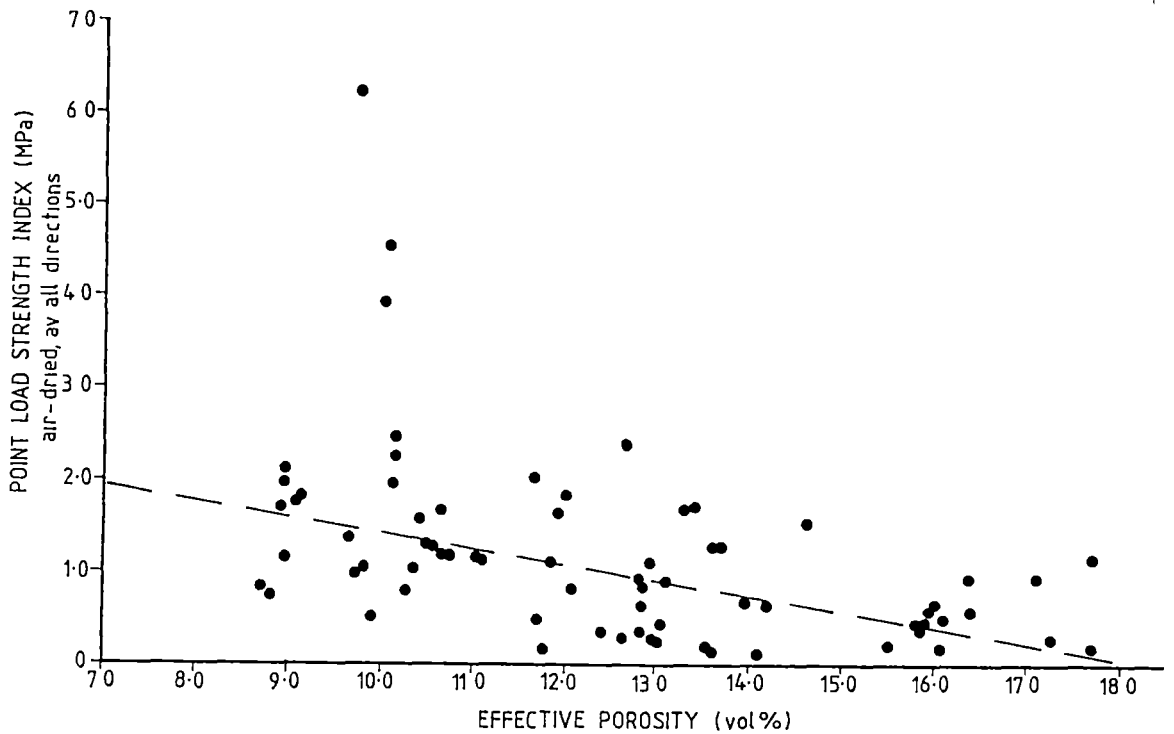


Figure 7.15 Correlation between strength and porosity in Tasmanian building sandstones. Data source: Appendix One, including all individual specimens for which both strength and porosity were measured (all geological associations). Both fresh and weathered specimens are included.

property determined by certain more fundamental properties (pore space, micro-fracturing and clay content) which also happen to partly control strength, rather than to consider porosity *per se* as a property which determines strength.

(F) Micro-fracturing

Micro-fracturing causes a reduction in stone strength by disrupting intergranular bonds. It can be considered as a secondary feature which is super-imposed upon the intergranular texture which is the primary determinant of sandstone strength.

Micro-fracturing may be caused by poor quarrying or processing techniques (see Section 5.4.1). Natural micro-fracturing is known to occur in some rock types (eg, granite); however the degree to which it may affect Tasmanian sandstones has not been determined. Micro-fractures in sandstone may be very difficult to recognise under the microscope (Spry 1976).

(G) Mineralogy

Sandstone strength is influenced by the strength of the constituent minerals. Quartz, the dominant constituent of Tasmanian building sandstones, is very strong. Feldspar and ferruginous cement (goethite) are somewhat weaker, while clay and mica are the weakest common components.

The strength of quartz is not a limiting factor in sandstone durability; metamorphic quartzites consisting of close to 100% quartz are generally too strong for practical building

use. Thus, a small proportion of weaker intergranular bonds (clay) is actually necessary to keep sandstone strength within workable limits. It would be interesting to determine the proportion of intergranular clay bonds necessary for this purpose; such a sandstone would be the ideal building material, having the optimum balance between durability and workability.

Since the great majority of clasts in Tasmanian building sandstones are strong quartz, the real determinant of sandstone strength is considered to be the nature of the bonds between quartz clasts, ie, whether quartz, clay, ferruginous or other bonds (Spry 1976, 1983). Quartz-quartz bonds are the strongest. Increasing proportions of ferruginous cement will increase strength to some degree provided it replaces clay bonds or fills pore spaces rather than replacing the stronger quartz bonds. Conversely, increasing proportions of weak clay bonds will decrease stone strength.

Although a higher proportion of quartz clasts will create more opportunities for strong quartz-quartz intergranular bonding, there is not necessarily a direct correlation between the total volumetric content of a particular mineral in the stone, and the degree of bonding produced by that mineral type. Thus, a given quantity of clay may occur predominantly as interstitial fillings (in which case it causes minimal lowering of stone strength), or as intergranular layers and films (in which case it may lower strength significantly).

It is therefore considered that the total volumetric proportions of quartz, clay and ferruginous minerals are only crudely correlated with stone strength, in that the presence of greater quantities of a particular mineral will tend to produce more intergranular bonding of that particular type. However, a full understanding of stone strength must involve actual determination of the proportions of particular intergranular bond types.

Minor mineral types such as feldspar and mica constitute weaker clasts, and may lead to a reduction of stone strength if present in sufficient quantities. However these are generally a minor consideration in the strength of Tasmanian building sandstones, except in the case of laminae of concentrated mica grains (see below).

The abundance of detrital quartz in Tasmanian sandstones is considered in Section (7.8.1), whilst the occurrence of authigenic quartz is discussed below. Controls on the abundance of clays are discussed in Section (7.8.3), while those on feldspar and mica are discussed in Sections (7.8.2) and (7.8.5) respectively. The abundance of ferruginous cement is considered to be related to the presence of Fe-rich clay minerals, and to the proximity of intrusive dolerite bodies (see Sections 7.6 and 7.8.4).

(H) Laminae

Thin laminae in sandstone are a macroscopic feature which cause a distinct strength anisotropy resulting in easy splitting along the laminae. Such laminae may comprise one or more of the following features:

- Concentrations of clay, mica or graphite.
- Elongate quartz grains having a strong common orientation of their long axes.
- Strong common alignment of clay masses around quartz grains.

Such laminae are characteristic of strongly bedded sandstones (cross- or planar-bedded). Massively bedded sandstone is therefore preferred for most applications, since it is less prone to the occurrence of splitting laminae.

(I) Intergranular bonds: Introduction

As noted above, sandstone strength is primarily determined by the strength and proportions of the bonds between the quartz grains (the "Intergranular Texture", see also Section 2.3.4).

Quartz bonds are the strongest type, both because of the greater strength of quartz, and also because the bonding quartz may grow in crystallographic continuity with quartz grains, providing the strongest adhesion (Dapples, *in* Larsen & Chilingar 1979). Note, however, that the presence of thin "dust-rings" consisting of early clay or ferruginous coatings, may dramatically lower the strength of quartz bonds by interposing a weak film between the detrital quartz clasts and the authigenic quartz cements.

Ferruginous cements are weaker materials, and provide poorer adhesion to quartz grains, since they have crystallographically discordant boundaries with the quartz grains (Dapples *Ibid.*). Clay is a still weaker material, and produces the weakest bonds. Clay bonds are prone to significant weakening with wetting.

Quartz bonds may be of two basic types: welded boundaries produced by appression and interpenetration of quartz grains, causing pressure solution of silica, and cemented boundaries produced by precipitation of authigenic silica. Spry (1976) was not able to find any difference in strength between the two types. Both welded boundaries and authigenic quartz cements were very commonly noted in Triassic and Permian sandstones during this project, although relative proportions of the two types were not determined.

(J) Intergranular bonds: quartz grain welding

Welding of quartz boundaries occurs as a result of appression of quartz grains during compaction of the sediment. Pressure solution may occur along the appressed boundaries, causing dissolution of silica which may be redeposited elsewhere as authigenic cement. At the same time, interpenetration and strong bonding of the appressed grains along curved, irregular, sutured or straight boundaries occurs, producing increased interlocking of quartz grains, and a stronger, denser texture overall. The phenomenon of grain welding in sandstones is related to processes of lithification and diagenesis rather than to metamorphism (Spry 1976).

Dapples (*in* Larsen & Chilingar 1979) considers straightline (bilateral or triple-grain junction) welded boundaries to be the strongest; these are produced by extended phases of strong compaction and pressure solution. Pressure solution has been reported (McBride 1989) to be most extensive in very fine sandstones, and of decreasing significance in medium and coarse-grained sandstones.

Since Tasmanian Triassic and Permian sandstones have not been subjected to orogenic conditions, the major cause of pressure solution and grain welding has probably been simple overburden pressure. McBride (1989) notes that the shallowest burial depth at which pressure solution has been reported in sandstones is 600 metres (in Brazil), but most reports indicate that burial of greater than 1500 m is needed to initiate significant pressure solution. Such burial depths were probably attained by Tasmanian Early Triassic and Permian sandstones (see Everard, *in* Turner & Calver, 1987, p.144).

It is likely that the deepest buried (oldest) sandstone horizons will have experienced the greatest overburden pressures, and so will exhibit the highest proportion of welded quartz-quartz grain boundaries. Thus, the Permian and lowest Early Triassic sandstones should be strongest in terms of welded grain boundaries.

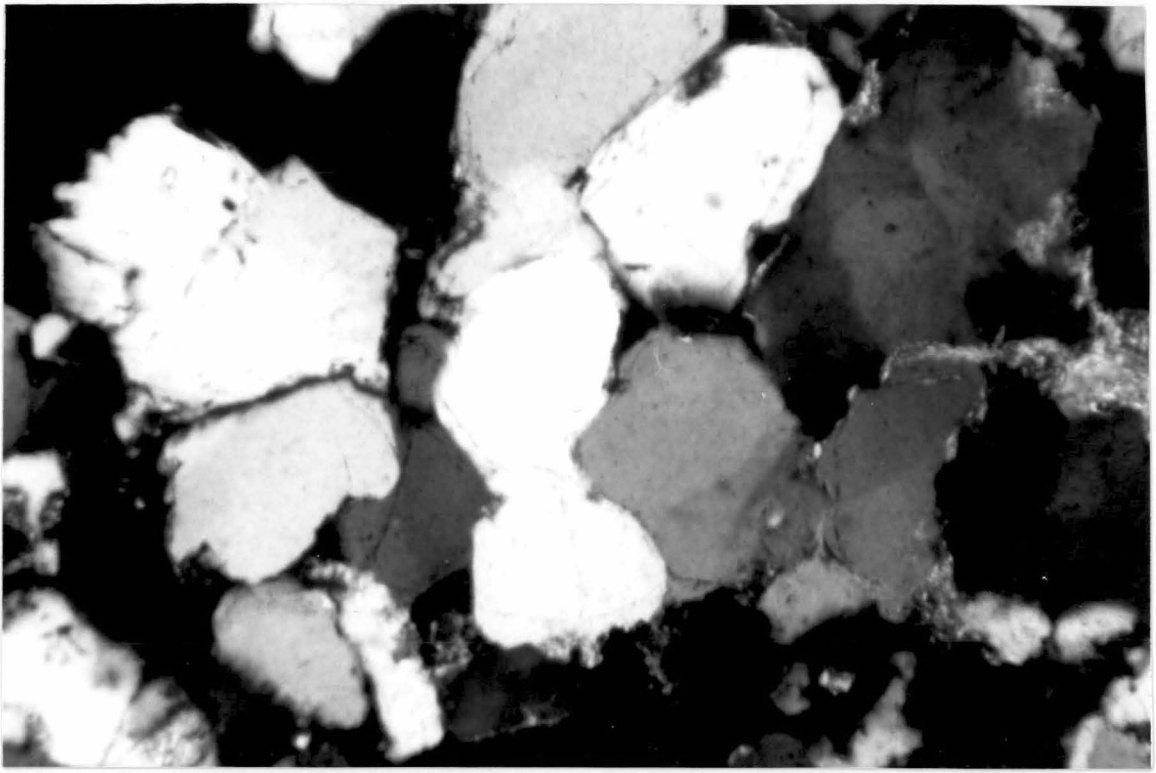


Plate 7.23 Quartz bonding: abundant quartz cement indicated by "dust rings". Grain welding indicated by irregular appressed boundaries. Note minor intergranular clay layer ("speckled", RHS). Specimen C/1/2, Cobbs Hill Quarry, Source 23; scale x 100, crossed nicols.

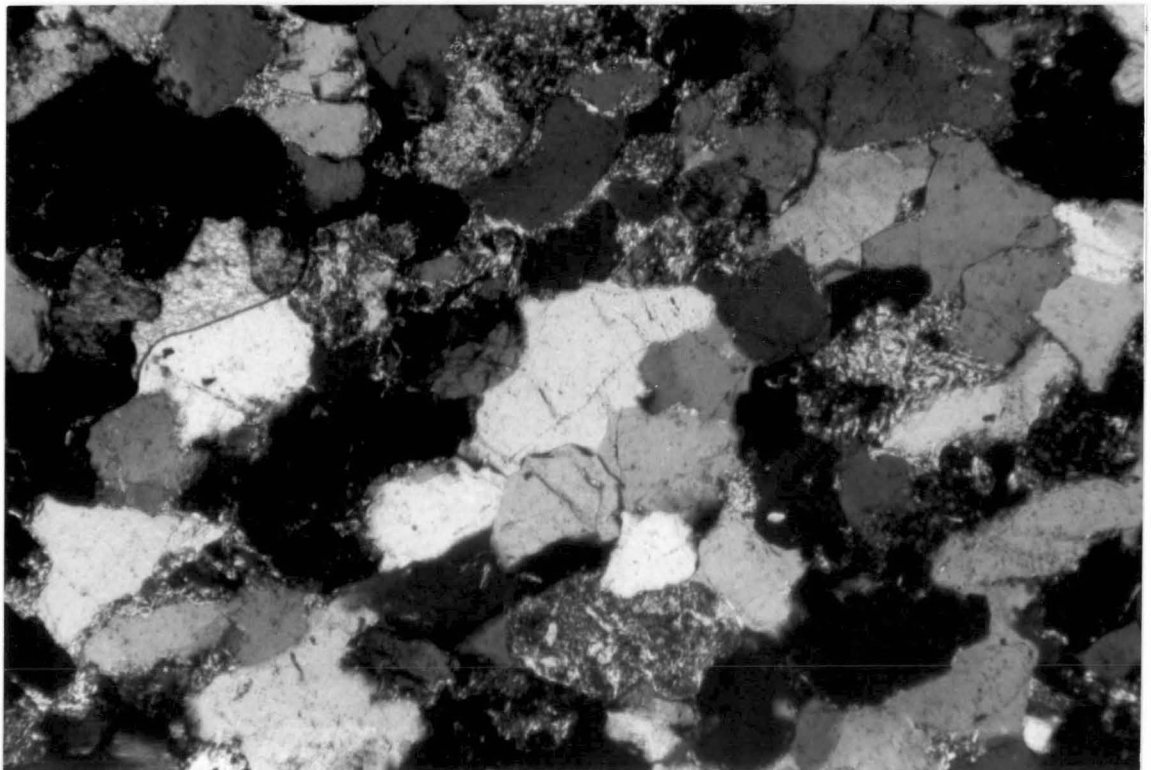


Plate 7.24 Clays ("speckled" masses): pellet at lower centre, intergranular layers and films at upper centre and lower LHS, interstitial masses (possibly deformed pellets) at RHS and upper centre. Specimen FB 1, Molesworth Quarry, Source 29; scale x 100, crossed nicols.

However, the main phase of quartz cementation is considered to occur at shallower burial depths than the main phase of pressure solution (see below). Since quartz cementation has the effect of restraining compaction (Scherer 1987), increasing burial depths after cementation may only result in a marginal increase in the degree of pressure solution and grain welding. Thus, variations in stone strength due to variations in the degree of grain welding probably have a less important effect on strength than variations in the degree of quartz cementation (such as may occur during uplift, due to regional heating events for instance: see below).

These speculations have not been tested, but could be assessed by using microscopic line traverse methods (see Appendix Three) to determine the relative proportions of welded and cemented boundaries in Tasmanian sandstones from a wide range of stratigraphic heights and geographical locations in the Permian and Triassic sequences. Types of welded boundaries (ie, irregular or straightline) should also be measured.

(K) Intergranular bonds: authigenic quartz cement

Authigenic quartz cement (syntaxial overgrowth) is very common in Tasmanian Early Triassic and Permian sandstones, and has been observed in hand specimen (glittering crystal faces), and by both optical and electron microscopy. Scanning Electron Microscopy (see Section 7.8.3) shows an abundance of well-formed quartz crystal faces growing into pore spaces, and commonly overgrown by later authigenic clays. This indicates that the main phase of authigenic quartz cement precipitation was prior to the most recent phases of clay authigenesis.

Eggert (1983) has distinguished three phases of diagenesis in Tasmanian Triassic Sandstones. These correspond to Eggert's three phases of clay authigenesis (see Synthesis of Section 7.8.3):

- 1) Clay rims form on detrital grains. Beginning of mechanical compaction. Quartz overgrowths start to form on detrital grains, some lithic fragments and brittle feldspars crushed between quartz grains.
- 2) Extensive precipitation of quartz overgrowth cement. Porosity reduced. Compacted mudstone fragments recrystallise to form intergranular pseudo-matrix clay cement.
- 3) (In carbonate-free sandstones, eg, Quartz Sandstone Sequence) Porosity reduction continued by alteration of feldspar grains to clay, and continued formation of clay as pore-lining and pore-filling cement.

Eggert's study suggests that the precipitation of quartz cement primarily occurred during burial, prior to late stage uplift. This concurs with the SEM evidence noted above.

The following are possible sources of dissolved silica for the production of authigenic quartz cement in Tasmanian sandstones:

- 1) Silica dissolved by pressure solution during formation of welded quartz grain boundaries during deep burial (Leder & Park 1986, McBride 1989). Silica may be dissolved through pressure solution in the sandstone bodies themselves, adjacent shales, and potentially also from much more deeply buried shales undergoing low-grade metamorphism, with subsequent upward migration of silica-rich fluids (McBride 1989).

McBride notes that in many sandstone bodies there is evidence that silica cementation took place before pressure solution occurred in the same bodies. This suggests that pressure solution occurs at a greater depth than cementation, and that the silica released by the pressure solution may rise a significant distance through the sedimentary pile before precipitating in shallower sandstone horizons where the chemical conditions are suitable.

- 2) Silica released during deep-burial breakdown of feldspars, kaolinite and smectite (see Section 7.8.3, Fig. 7.11). The resulting precipitation of relatively silica-poor illite or chlorite from these precursor minerals leaves significant quantities of silica in solution (Siever 1982, Leder & Park 1986, McBride 1989).

Siever, Leder & Park, and McBride suggest that the silica dissolved in this fashion will largely be released by the alteration of clays in adjacent shale beds, and will then be transported into the sandstone by groundwater flow. Adjacent shales (eg, in underlying Permian lutite horizons) may indeed be such a source of silica in Tasmanian sandstones. However, the presence of the necessary precursor minerals, and their diagenetic products, in the Early Triassic sandstones suggests that at least some of the dissolved silica formed in this manner comes from clay diagenesis processes within the sandstones themselves.

- 3) Silica dissolved by reaction between pore fluids and detrital quartz grains, unrelated to pressure solution (Leder & Park 1986). McBride (1989) regarded this as a somewhat doubtful source of large quantities of silica cement.
- 4) Silica dissolved from silicates (clays, feldspars, micas, etc) in the zone of weathering, and then circulated to depths of up to several kilometres by deep-circulating meteoric waters (McBride 1989). McBride considers it likely that this form of quartz cementing is important in intracratonic and foreland basins.

McBride (1989) lists a number of other possible minor silica sources, but those listed above are the ones most likely to be important in Tasmanian Triassic and Permian sandstones.

It has been found that many sandstone bodies contain more silica cement than can be accounted for by possible silica sources within the bodies themselves (Leder & Park 1986, McBride 1989). It is considered (McBride 1989) that the silica cement in most sandstone bodies is derived from a number of sources, including the sandstones themselves, associated shales, deeper buried sandstones and shales undergoing pressure solution and clay diagenesis, and much more deeply buried siliclastic rocks undergoing metamorphism. Deeply circulating meteoric waters may also provide a large amount of silica in some sedimentary basins.

Silica solubility increases somewhat with increasing pH (Fairbridge, *in* Larsen & Chilingar 1967, Fig. 7). However, the solubility of silica is essentially constant at pH values 2 through to 8.5, only increasing markedly at higher pH values (Larsen & Chilingar 1979, Ch. 3). Thus, Leder & Park (1986) consider silica solubility to be essentially independent of the pH in aqueous solutions over most of the geologically meaningful range. Silica solubility also has only a minor dependence on salinity in normal formation waters (*Ibid.*).

Temperature is the primary control on silica solubility (Leder & Park 1986). Silica solubility rises markedly with increasing temperature. In the laboratory, the following equilibrium saturated solutions have been attained (Larsen & Chilingar 1979, Ch. 3):

100 -150 ppm	SiO ₂ in solution at 22 - 27° C
>600 ppm	SiO ₂ in solution at 150° C

Under conditions of constant geothermal gradient, the temperature of sandstone pore waters is dependant on the depth of burial. Studies of quartz cementation in a large number of sandstone bodies (McBride 1989) indicate that the most common pattern is that little quartz cementation occurs shallower than 1 km, that the most active zone of cementation is between 1 & 2 km (over a temperature range of about 40° - 90° C), and that less cementation occurs below these depths.

The degree of quartz cementation which occurs is considered (McBride 1989) to be partly dependant on the rate of burial subsidence, since most cementation occurs during the period in which the sandstones reside in this "silica mobility window". During residence in the window, silica precipitates out of rising (and cooling) formation waters which have become charged with silica (dissolved from sources such as those outlined above) at greater depths where temperatures are higher. The rising of the formation waters occurs due to compaction and de-watering of the deeper sediments, and also due to deep convection circulation. There may also be some mixing with silica-rich deeply circulating meteoric waters in intracratonic basins.

Thus, by comparison with many other sandstone bodies throughout the world, it is likely that most of the silica which cemented the Early Triassic and Permian sandstones of Tasmania was derived from a combination of the sources listed above, dissolving silica into the pore-waters at greater depths where temperatures were higher, and was deposited during upwards movement and cooling of silica-rich waters.

No direct evidence has been obtained as to the particular sources of authigenic silica in the Tasmania Basin, and no attempt has been made to determine the quantities of dissolved silica required to account for the observed quantities of quartz cement. In the absence of such evidence, the models presented above are considered to be the most likely processes of silica authigenesis in Tasmanian sandstones. Direct evidence of the temperatures (and by inference, the depths) at which quartz cementation occurred could be obtained from oxygen isotope and fluid inclusion studies of the quartz overgrowths (McBride 1989, Walderhaug 1990).

Given that processes such as those outlined above would probably be pervasive throughout the Early Triassic and Permian sandstone horizons of the Tasmania Basin, the potential for quartz cementation under normal geothermal gradients during burial and the initial stages of uplift appears to be fairly constant throughout these horizons.

However, it is likely that the occurrence of discrete regions of higher-than-average geothermal heatflow within the Tasmania Basin could lead to increased quartz cementation, beyond that achieved simply as a result of burial under normal geothermal gradients. If a region of high heat flow developed at any stage of burial or uplift, additional silica would be dissolved from the sources postulated above, and then precipitated as the pore waters moved closer to the surface and cooled. Due to the higher heatflow, the depths of both silica dissolution and cementation would be closer to the surface than would be the case under normal heatflow conditions.

Potential sources of higher-than-normal heatflow within the Tasmania Basin include phases of igneous intrusion (Jurassic dolerites and Tertiary basalts), and heatflow associated with Tertiary rifting zones.

Intense silicification due to heating and cooling, leading to hornfels formation, is common in the contact metamorphic aureoles of dolerite and basalt intrusions in Tasmania (the Kingston Quarry sandstone (Source 31) is a hornfels which has been produced by nearby dolerite intrusion). However, this contact effect has only been observed within a few metres of intrusive contacts (see Section 7.4.1 B).

The widespread intrusion of Jurassic dolerite into the Tasmania Basin (and adjacent parts of Antarctica) is considered to be an early precursor of the breakup of Australia and Antarctic. In accordance with the model of Falvey (1974), this early stage may have been accompanied by higher regional geothermal heatflows affecting the entire Tasmania Basin.

The Tertiary basalts of Tasmania were intruded after the main phase of the Cretaceous-Early Tertiary faulting which produced the major horst and graben structures in the Tasmania Basin (Sutherland *et al.*, in Burrett & Martin 1989, p. 395). Sutherland *et al.* suggest that the basaltic vulcanism is related to Tasmania having migrated across a thermal upwelling related to the initiation of the Tasman rift (east of Tasmania), which remained extant as a line of slowly decaying thermal cells (or hot spots). Such hot spots could potentially have caused increased or re-juvenated quartz cementation in the Tasmania Basin, associated with the major regions of basaltic intrusions.

The Late Cretaceous and Early - Mid Tertiary faulting in the Tasmania Basin, and adjacent regions, produced a series of horsts and grabens (see Fig. 7.2). Of these, the Tamar Graben and associated basins are extensions of the offshore Bass Basin which was initiated in Late Jurassic-Early Cretaceous times. The whole period of basin formation was a phase of rifting associated with the breakup of Australia from Antarctica (Morrison *et al.*, in Burrett & Martin 1989, p.341).

The initiation of the rifting of Australia and Antarctica is considered to have been associated with thermal upwelling (Falvey 1974). Middleton (1982) has shown that vitrinite reflectance values obtained from the Bass Basin indicate a geothermal gradient in the basin during the Tertiary which was about $10^{\circ}\text{C km}^{-1}$ higher than the present day geotherm.

Although the present writer does not know of similar studies in the onshore extensions of the Bass Basin, and other rifting-associated grabens such as the Derwent Graben, it seems likely that the graben basins in the onshore Tasmania Basin would have experienced similarly elevated geothermal heating during the Tertiary. Such heating is likely to have produced a phase of rejuvenated quartz cementation of the Triassic and Permian sandstones within the Derwent, Coal River, Tamar and other grabens.

It is notable that the Cobbs Hill, Linden and Molesworth sandstones, all of which fall within the Derwent Graben, are amongst the strongest Tasmanian sandstones known to date. Qualitative examination of thin sections of the Cobbs Hill sandstone (see Appendix Two) indicates an unusually high proportion of authigenic quartz overgrowths (see Plate 7.23).

As noted in Section (7.4), however, the Tertiary Grabens are also considered to be zones of more intense jointing. Stones of higher than average strength within the grabens would therefore be expected to have higher than average joint densities!

The best exploration targets for high-strength and widely-jointed sandstone may therefore

be areas outside grabens, which have experienced a lower intensity of Tertiary faulting, but which have experienced increased quartz cementation in regions of higher geothermal gradients caused by moving over hot spots which produced the Tertiary basaltic intrusions. The writer has no data on the degree to which such hotspots might have elevated geothermal gradients in the uppermost parts of the crust where the Tasmanian building sandstone sequences were residing during the Tertiary.

The occurrence of phases of rejuvenated quartz cementation due to heating events subsequent to the main phase of burial-related heating could be established by looking for oxygen isotope and fluid inclusion zonation in quartz overgrowths (McBride 1989, Walderhaug 1990). The occurrence of an inner overgrowth zone characteristic of deep burial temperatures and pressures, overgrown by zones characteristic of one or more subsequent - and different - heating events at shallower depths, would constitute evidence of such secondary quartz cementation events.

According to McBride (1989), surface and shallow subsurface meteoric waters are commonly supersaturated with respect to quartz (as discussed above, it is considered that in some basins such silica-rich meteoric waters may circulate to significant depths and thereby contribute to silica cementation in the deep sub-surface "silica mobility window"). However, in near-surface deposits such waters generally produce only small amounts of silica cement (<3% in most fluvial sandstones), except in certain special circumstances under which silcretes form (McBride 1989). Silcretes have not been noted in Tasmanian building sandstone outcrops.

Surface evaporation of groundwater is one means by which the silica in shallow meteoric waters may be precipitated (McBride 1989). It is likely that such surface evaporation causes small amounts of silica precipitation in the "case-hardened" surface "rinds" of Tasmanian sandstone outcrops. The breakdown of feldspars, micas, smectites and illites during surface weathering and kaolinisation (see Section 7.8.3) may release the silica which causes the surface waters to become silica-supersaturated; the silica is then deposited within a few millimetres of outcrop surfaces where evaporation forces precipitation to occur.

It is unclear whether actual dissolution of quartz grains might occur in near-surface outcrops. Since quartz is most soluble at high pH and relatively elevated temperatures, it appears unlikely that significant dissolution of pre-existing crystalline quartz would take place under the relatively cool, and neutral to slightly acid conditions occurring in surface or near-surface outcrops affected by meteoric waters.

(L) Intergranular bonds: ferruginous cement

The origin and distribution of ferruginous cements in Tasmanian sandstones has been discussed in Sections (7.6.3 B & C), (7.6.4), (7.8.3), and (7.8.4). From the point of view of building stone studies, the most important effect of ferruginous cement is considered to be its control over stone colour.

As a cement, it is weaker than quartz, and generally present in much smaller quantities (1-10% by vol.) than the weak clay bonds (typically 10-25% by vol.). Whilst increasing proportions of ferruginous cement may play some role in increasing stone strength (eg, see Spry 1983,p.30), the present writer considers that the strengthening effects of ferruginous cement will normally be greatly outweighed by the combined effects of quartz and clay bonding. See Plate (7.26).

The Buckland Quarry (Source 28) gives an instructive example of the relatively small effect of ferruginous cementing on stone strength. In this quarry, patches of stone with abundant ferruginous-cement Liesegang Ring banding occur as discrete areas within beds of uniformly coloured grey-white stone containing very little ferruginous cement.

The ferruginous-banded stone has a significantly higher clay content (probably due to kaolinisation under the conditions of increased groundwater flow which also produced the Liesegang Rings). Largely as a result of the higher clay content, the banded stone has a significantly higher porosity, and a lower average strength, than the grey-white unbanded stone (see Appendix One).

Any strengthening effect of the ferruginous cement in the Buckland Quarry stone is completely overshadowed by the much greater effect of clay bonding.

(M) Intergranular bonds: clay

Whereas an increasing proportion of quartz intergranular bonding is the major property causing increased sandstone strength, an increasing proportion of clay bonding between sand grains is the major influence leading to a decrease in strength (Spry 1976, 1983). The clay may be present as either interstitial fillings and pellets, or as intergranular layers and films; the latter mode of occurrence causes the greatest degree of strength loss (see Sections 2.3.4 and A 3.2.3). See Plates (7.24, 7.25)

The origin of clays, and the causes of variations in total clay content, in Tasmanian building sandstones has been considered in Section (7.8.3). In the context of the present discussion it is necessary to consider the controls on the mode of occurrence of clay within sandstones; ie, what causes the clay to occur as either interstitial or intergranular fillings.

During the original phase of deposition, much of the detrital clay will be deposited as pellets and amorphous interstitial pore-filling masses. During subsequent diagenesis and weathering processes, a significant proportion of the authigenic clays will also be deposited as interstitial pore-lining or pore-filling masses.

Possible means by which intergranular layers or films may form include the following:

- 1) Deposition: A small proportion of detrital clay may coat sand grains during deposition, or be squeezed inbetween sand grains during very early phases of burial, so producing intergranular layers or films separating sand grains.
- 2) Early burial diagenesis: Early precipitation of authigenic clays, prior to precipitation of authigenic quartz cements, may produce thin clay coatings around some sand grains, which inhibit later quartz cements from precipitating in direct crystallographic continuity with the detrital quartz grains. These coatings may be preserved as dust-rings and intergranular films.
- 3) Compaction: During burial, overburden pressure will cause compaction of the sediment. The clay pellets and interstitial fillings, being rather plastic, will be deformed and squeezed inbetween sand grains, forming intergranular layers and films. Most of this squeezing will probably occur prior to the main phase of quartz cementation; once cementation has occurred, the cements binding sand grains together will provide little opportunity for further clay to be squeezed between the grains.

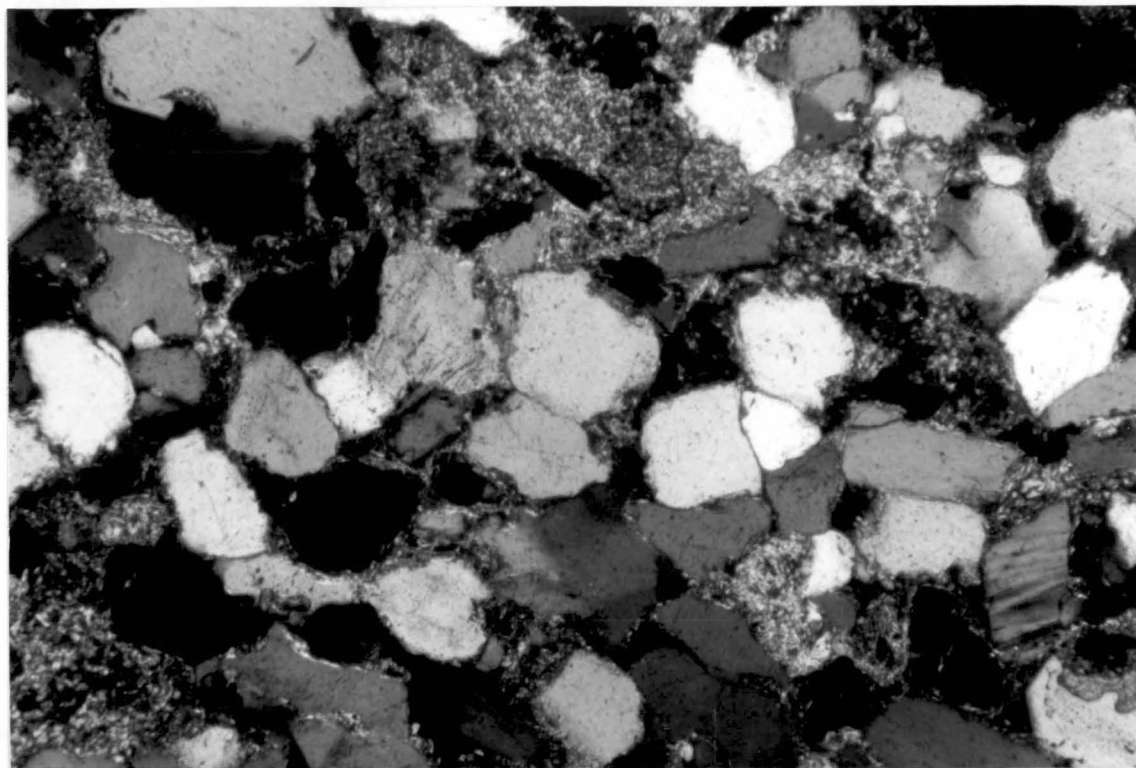


Plate 7.25 Very high total proportion of clay ("speckled" masses) in smectite-rich sandstone (weak intergranular texture). Specimen SM 1, Kangaroo Point Green Sandstone Quarry, Source 4; scale x 100, crossed nicols.

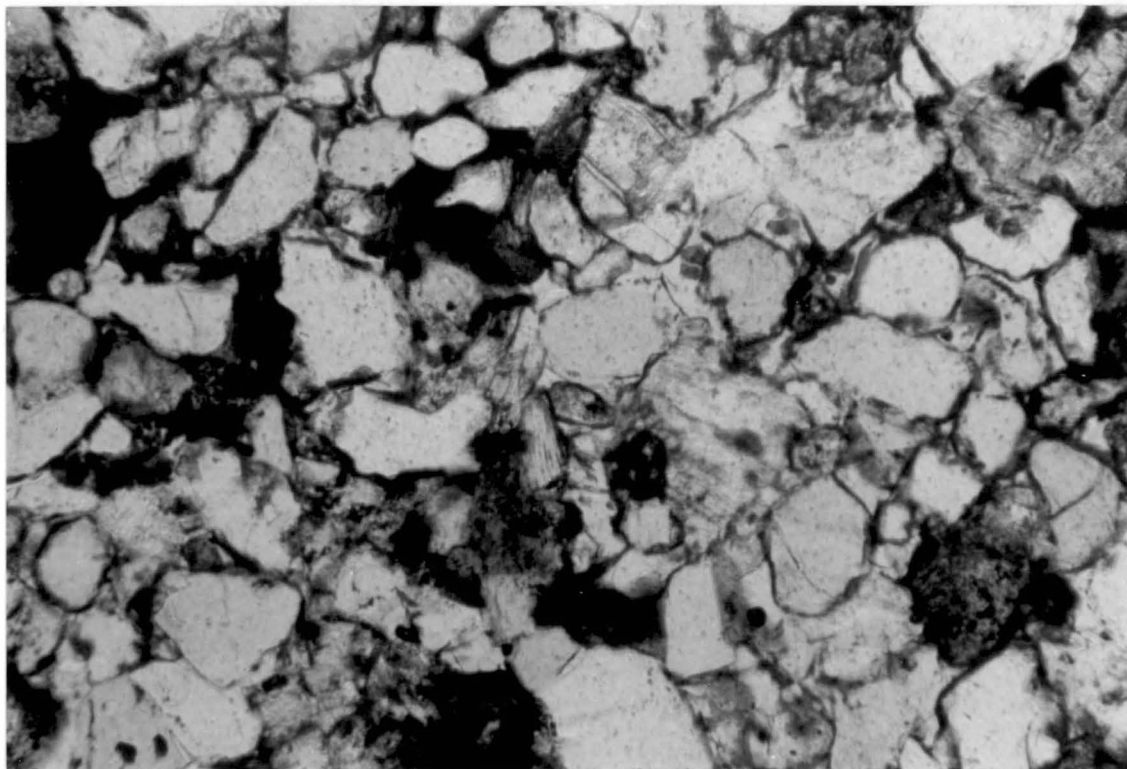


Plate 7.26 Abundant ferruginous cement (dark masses in interstitial spaces and lining quartz grains). Specimen Riz 1, Oatlands Quarry, Source 24; scale x 100, plane light.

It is considered likely that this is the main mechanism by which intergranular clay layers and films are formed. The degree to which such intergranular layers are formed is probably dependant on the proportion of clay in the sediment prior to compaction, and the degree of compaction which occurs prior to quartz cementation.

- 4) Uplift and near-surface weathering: During late stages of uplift, the overburden pressure is released, and so there is a relief of the pressures forcing individual sand grains to remain pressed against one another. If a small amount of silica dissolution were to occur along grain boundaries or at the junction between quartz overgrowths which are not crystallographically continuous, then late-stage authigenic clays would have an opportunity to precipitate along the fine discontinuities so created. These would result in an increase in intergranular clay films.

However, as indicated in the discussion of quartz cementing above, there appears to be little evidence of quartz dissolution in near-surface sandstones. The suggested process is therefore considered unlikely to be significant.

No attempt was made in this project to produce evidence for any of these processes (or others) having occurred. In the absence of such a study, it is not possible to produce any guidelines to the prediction of bodies of sandstone having high or low proportions of intergranular clay, other than to propose that sandstones having the highest total clay content prior to compaction and quartz cementation, are those likely to have the greatest proportion of intergranular clay layers and films.

Summary of sandstone properties yielding high strength

The sandstone properties which yield high strength are essentially those which contribute to a good intergranular strength. A combination of the following properties would be most likely to produce a high strength sandstone with minimum strength anisotropy and minimum strength loss upon wetting:

- Fine grainsize (questionable influence in Tasmanian building sandstones).
- Well sorted grainsize distribution.
- Low porosity.
- High quartz content, low clay content.
- Absence of bedding laminae, particularly where lined with mica, graphite or clay .
- High proportion of welded and interpenetrating quartz-quartz grain bonds .
- High proportion of authigenic quartz cement.
- Low proportion of intergranular clay layers and films relative to interstitial clay content.

7.9.2 Dimensional Instability

Dimensional instability (Spry 1988) is manifested as temporary or permanent changes in the physical dimensions of stone blocks in response to heating/cooling and wetting/drying cycles (see Section 2.5.9). Dimensional instability depends on the co-efficient of thermal expansion of minerals in the stone, and upon the propensity of those minerals to expand upon wetting.

Since quartz and clays comprise over 90% of most Tasmanian building sandstones, the properties of these minerals are most important in this regard. It is considered that the propensity of clays to expand upon wetting is the primary cause of dimensional instability in Tasmanian sandstones. Whilst smectites show the greatest degree of expansion upon wetting (intra-crystalline expansion, Gillot 1987), other clays will expand to some degree through inter-crystalline expansion (see Section 2.2.4).

Sandstones with a high proportion of rigid quartz-quartz intergranular bonds will tend to resist the expansion of wetted interstitial clay. However, where a high proportion of grain bonds are in the form of intergranular clay layers and films, marked expansion of the clay/sand aggregate as a whole can occur upon wetting. It is therefore considered that high dimensional instability in Tasmanian sandstones is related to high proportions of intergranular clay, the instability being highest where smectite is a significant component of the intergranular clays.

The highest degree of dimensional instability measured in Tasmanian sandstones to date has been found in the massive Elderslie Quarry stone (Source 26). This stone is characterised by a rather high proportion of intergranular clay layers and films (see Section 5.4.2).

The occurrence of a high degree of dimensional instability in Tasmanian sandstones is thus closely related to the same properties which produce a low stone strength and a high degree of strength loss on wetting (see Section 7.9.1).

7.9.3 Keys to location of strong, dimensionally-stable sandstones

Based on the criteria for high strength sandstones listed at the end of Section 7.9.1 (above), the following exploration keys to the location of high strength Tasmanian building sandstones can be proposed:

- Fine grainsize: In a broad way, grainsize decreases going upwards through the Early Triassic Quartz Sandstone Sequence as a whole, and also going upwards through individual fluvial deposition cycles. However, the desirability of fine grainsize must be weighed against other factors:

In Tasmanian Triassic sandstones, finer grain sizes tend to be related to higher clay contents (Section 7.8.1), and to thinner bedding (Section 7.5.4), and the desirable massive beds are also more prevalent in the lower, coarser, parts of individual cycles, and of the Quartz Sandstone Sequence as a whole (Section 7.5.4). Strong quartz-quartz grain welding is also considered likely to be more prevalent towards the base of the Quartz Sandstone Sequence (Section 7.9.1)

Within the range of fine to medium grain size, it is likely that decreasing grain size, in itself, is of little significance in controlling strength compared to other aspects of intergranular texture.

- Well sorted grainsize distribution: No data has been obtained on sorting variation within Tasmanian building sandstones, most of which fall within the range of moderately to well sorted (Section 7.7.1). It seems unlikely that sorting, in itself, would be a significant cause of strength variation within this range.
- Low porosity: Not considered as a fundamental property in its own right, being dependant on other fundamental properties which also simultaneously control sandstone strength (Sections 7.9.1, 7.10).
- High quartz content, Low clay content: The proportion of quartz in sandstone is a function of the proportion of detrital quartz plus diagenetic quartz cement. The latter is considered below; the highest proportions of detrital quartz will be found in sandstones with the lowest proportions of detrital and diagenetic clay (Section 7.8.1).

The highest proportions of clay are found in finer grained sandstones (Section 7.8.1), smectite-rich sandstones, and probably in sandstones having the highest proportions of relict detrital feldspar and mica (Section 7.8.3). Smectite-rich sandstones are most common in southeastern Tasmania (Section 7.8.3), and feldspathic/micaceous sandstones are most common towards the top of the Quartz Sandstone Sequence (Sections 7.8.2, 7.8.5). High proportions of authigenic kaolinite may occur in horizons which have been major aquifers, but the locations of such beds are difficult or impossible to predict.

Sandstones with a high proportion of ferruginous cement derived by breakdown of vermiculite clay may be relatively low in total clay content (Section 7.8.3).

- Absence of bedding laminae: Unless flagstone is specifically required, plane- or cross-bedded sandstone is undesirable; massive sandstone is desirable since it gives the lowest degree of strength anisotropy. Massive beds are more prevalent towards the base of individual depositional cycles, and towards the base of the Quartz Sandstone Sequence as a whole.
- High proportion of welded quartz-quartz bonds: Likely to be most prevalent in sandstones which have experienced the greatest depth of burial, ie, Permian and lowest Triassic sandstone beds (Section 7.9.1). However, variation in proportions of welded bonds is likely to be less important than variation in quartz cement proportions.
- High proportion of authigenic quartz cement: Likely to be most prevalent in sandstones which have experienced higher than average geothermal heatflow subsequent to the major phase of normal burial-related quartz cementation. Tertiary grabens and regions of basaltic intrusions related to mantle hot-spots are the most likely regions in which this may have occurred (Section 7.9.1).
- Low proportion of intergranular clay layers and films: Possibly largely a function of total clay content, being least prevalent in sandstones having lowest total clay (Section 7.9.1).

There is evidence that the occurrence of superficial polygonal "pachydermal" (or "elephant skin") fractures (see Section 2.4.6) on weathered outcrop surfaces may be an indicator of weak and dimensionally unstable sandstone.

Rigg (1970) studied examples of well-developed pachydermal fractures on Triassic sandstones on Bruny Island, and concluded that they are a result of surface stress-release during weathering. However, since it is manifestly obvious that not all sandstones show pachydermal fracturing upon weathering, there must be a factor which makes some sandstones more susceptible to this style of weathering than others. It is suggested here that the relevant factor is the degree of dimensional instability of the stone.

While the outcrops studied by Rigg (1970) have not been examined or tested during this work, an excellent example of superficial pachydermal fracturing occurs on outcrops of the massive sandstone bed within the Elderslie Quarry (Source 26).

As discussed in Section (5.4.2), the massive Elderslie stone is prone to rapid cracking upon exposure and removal of blocks from the quarry face. This appears to be the result of the stone shrinking significantly due to evaporation of its natural water content upon exposure, and seems clearly related to the fact that the stone has a high degree of dimensional instability resulting from an intergranular texture dominated by intergranular clay films (Sharples 1989b).

It can be hypothesised that the pachydermal fractures found on the natural outcrops of the same stone are formed in essentially the same manner. That is, due to exposure of the stone to atmospheric conditions at the outcrop surface, the drying out of the surface layer of stone results in the same marked shrinkage, causing a contractive straining of the surface stone which is relieved by polygonal cracking - the pachydermal fractures. In other words, stress-release by fracturing occurs.

It is noteworthy that cross-bedded sandstones overlying the massive bed at the Elderslie quarry do not show pachydermal fracturing on weathering surfaces. Significantly, the cross bedded sandstones contain a lower proportion of intergranular clay films, and are much more dimensionally stable than the massive stone (Sharples 1989b).

Interestingly, Forsyth(1989,p.27) notes that in sandstones towards the top of the dominantly sandstone interval of the Quartz Sandstone Sequence (Rp) in the Interlaken Quadrangle, a tendency towards finer grainsizes, lower quartz content and higher proportions of "brown matrix" (presumably iron-stained clay) is accompanied by the development of pachydermal fracturing. Sandstone of such a description could be expected to have more intergranular clay and thus be less dimensionally stable.

7.10 POROSITY AND DENSITY

Water is one of the dominant agents of sandstone decay (see Section 5.3). The entry of water into sandstone facilitates clay swelling, salt crystallisation, softening of intergranular clay bonds, and other decay processes. Since sandstone porosity is a measure of the amount of water which can enter a sandstone, lower porosities imply a lower susceptibility to water-related decay processes. Several studies have demonstrated a correlation between low durability and the combined effects of low strength plus high porosity (eg, Spry 1983, Section 6.3.1 of this thesis).

Sandstone porosity is therefore required to be as low as possible for maximum durability; recommended maximum porosities are given in Appendix Four.

"Effective Porosity" and "Water Absorption" are equivalent measures (by volume and weight, respectively), of the amount of water taken up by sandstone under conditions of 20°C and 1 atmosphere pressure (Section 2.5.1). As shown in the following discussion, the term "porosity" is in some respects a misnomer in the present context, since a certain proportion of the water absorbed by Tasmanian sandstones is actually taken up by expansion of clay masses, rather than by simple filling of void pore spaces. Nonetheless, for convenience the use of the term porosity will be continued, on the understanding that the property under discussion is actually water absorption.

"Absolute Porosity" refers to the maximum amount of water which can be taken up by a sandstone, generally under vacuum conditions. Absolute porosity is normally greater than effective porosity, due to the existence of very small or unconnected pores which water does not enter under normal conditions. In the following discussions, "porosity" refers to effective rather than absolute porosity.

7.10.1 Factors determining porosity and density of sandstone

Water may be held in sandstone in two different ways:

Open (void) pore spaces: Void interstitial spaces, micro-fractures.

Clay masses: Clays may have very high porosity (Ollier 1969 p.87, Pettijohn 1975 p.77, Spry 1983 p.49). Clay aggregates may absorb water into micro-pore spaces (eg, note the micro-pores evident in aggregates of authigenic illite, kaolinite and smectite in Plates 7.13, 7.15 and 7.19), by inter-crystalline swelling, and by intra-crystalline swelling of expanding clays such as smectite (Gillot 1987).

(A) The sources of porosity in Tasmanian sandstones

In many sandstones, the dominant source of porosity (or water absorption) is void pore spaces (eg, Tickell 1965, Griffiths 1967, Leder & Park 1986, Scherer 1987). For sandstones in which this is the case, porosity shows a linear inverse relationship to bulk density (Tickell 1965, Griffiths 1967 p.229).

Figure (7.16) plots the relationship between effective porosities and bulk densities of the Permian and Triassic Tasmanian building sandstones studied during the present work. It is clear that any relationship between these parameters in Tasmanian sandstones is, at best, very vague.

Two lines shown on Fig. (7.16) indicate the sort of relationship which would be expected between bulk density and effective porosity if the dominant source of porosity were open void spaces:

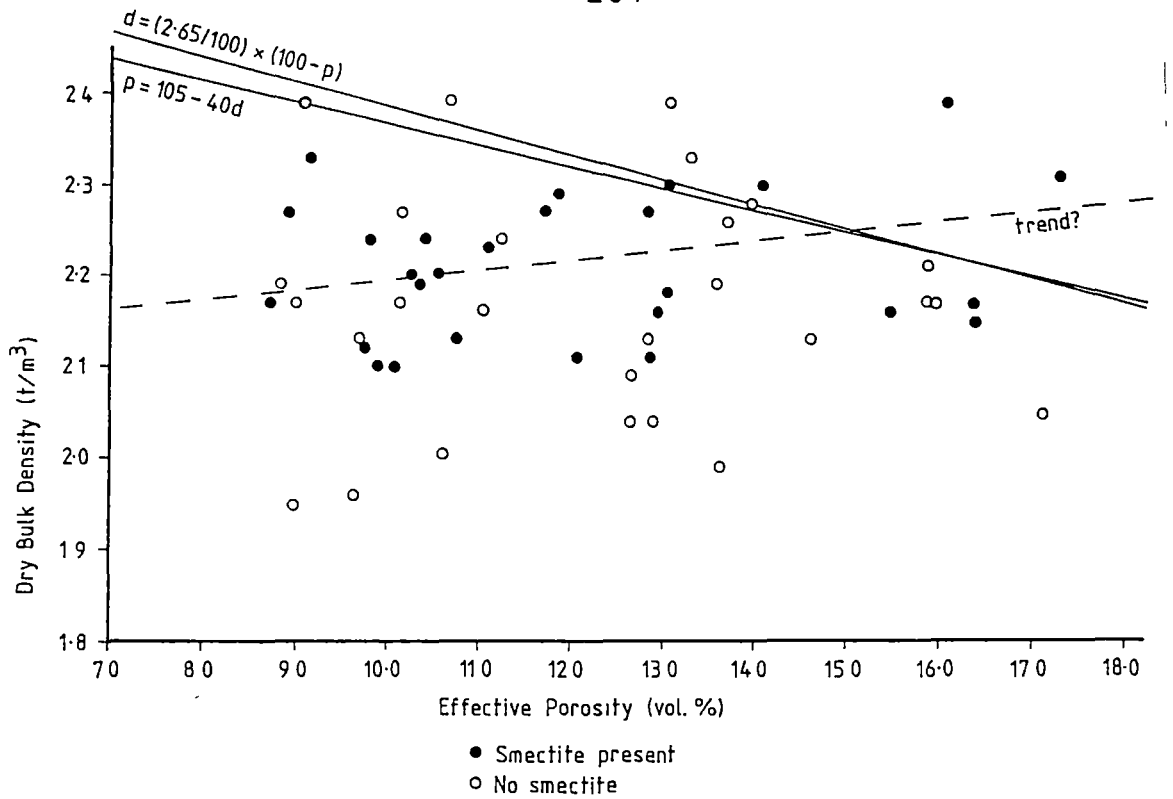


Figure 7.16: Relationship between dry bulk density and effective porosity in Permian and Triassic Tasmanian building sandstones. See text for discussion of trend lines. Data: Appendix One - all specimens for which porosity, density, total clay % and smectite % data available, excluding salt-affected specimens.

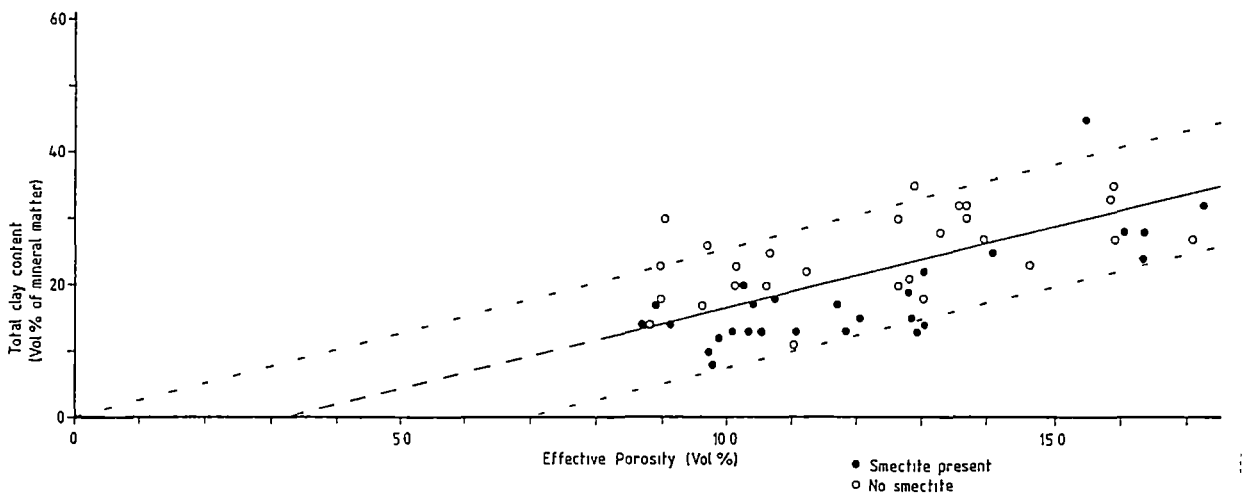


Figure 7.17: Relationship between total clay content and effective porosity for Permian and Triassic Tasmanian building sandstones. See text for discussion of trend lines. Data: as for Fig. 7.16.

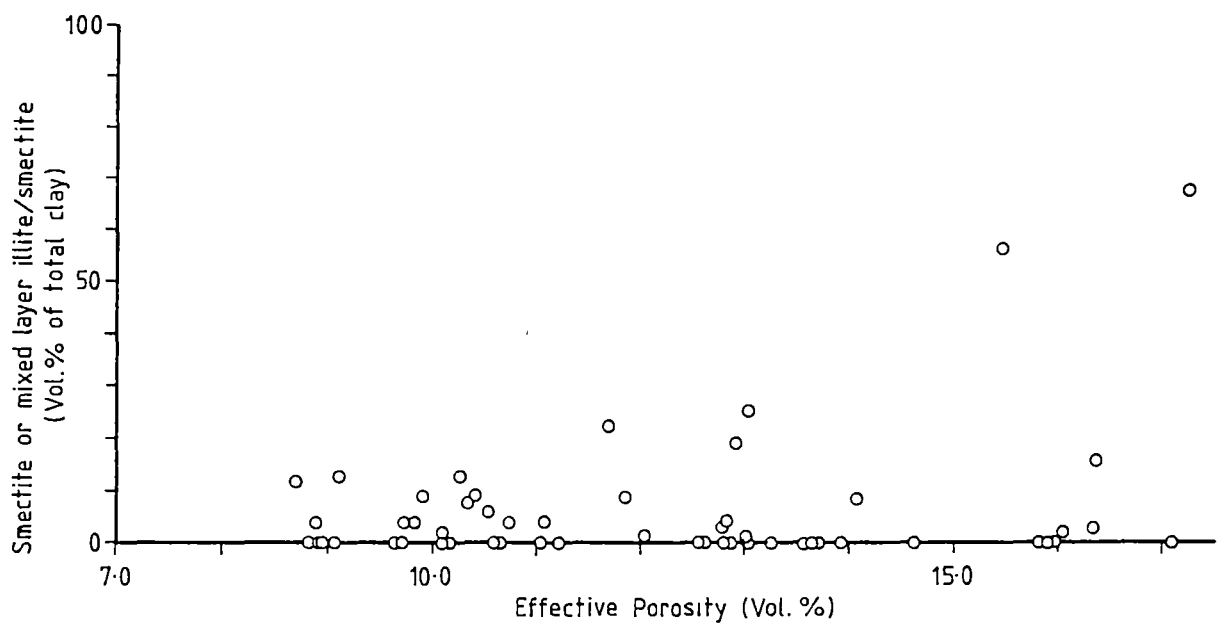


Figure 7.18: Relationship between smectite content and effective porosity in Permian and Triassic Tasmanian building sandstones. Smectite content presented as volume percentage of total clay.
Data: as for Fig. 7.16

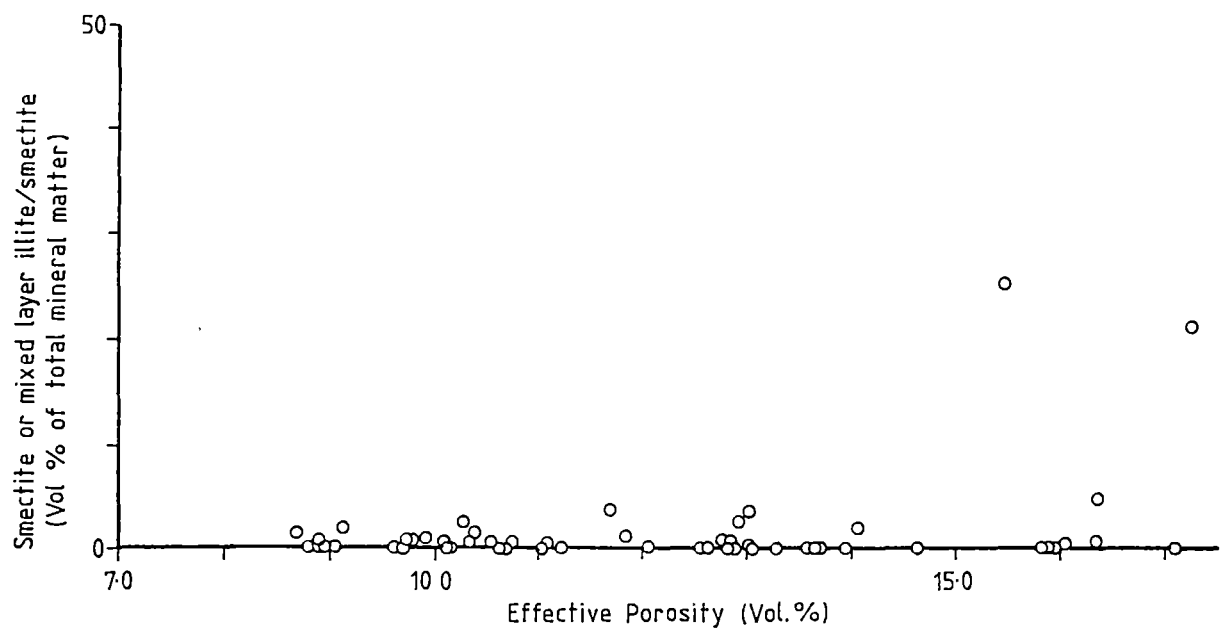


Figure 7.19: Relationship between smectite content and effective porosity in Permian and Triassic Tasmanian building sandstones. Smectite content presented as volume percentage of total sandstone mineral matter.
Data: as for Fig. 7.16

- 1) Since quartz and clays generally constitute over 90% (by volume) of the mineral matter in Tasmanian sandstones, the likely average specific gravities of the mineral matter can be reasonably estimated. Deer *et al.* (1966) give the following specific gravities for the common minerals in Tasmanian sandstones:

Quartz	2.65
Illite	2.6 - 2.9
Kaolinite	2.61 - 2.68
Smectite	2.0 - 3.0
Vermiculite	≈ 2.3

Since quartz is always the dominant mineral, and most clays have similar specific gravity (or slightly higher; Spry 1983, p. 60), it is reasonable to assume an average specific gravity of 2.65 for the mineral matter in Tasmanian sandstones.

Since the average dry bulk densities of Tasmanian sandstones are around 2.2 t/m³, it is clear that some void pore space does exist in these sandstones.

If the bulk densities of Tasmanian sandstones were simply an inverse function of void pore volume, then the following equation would hold true:

$$d = (2.65/100) \times (100-p) \quad \text{where:} \quad \begin{array}{l} d = \text{dry bulk density} \\ p = \text{porosity} \end{array}$$

This function yields a bulk density of 2.65 t/m³ where porosity = 0%, and a dry bulk density of 0.0 t/m³ where porosity = 100%.

This function is plotted on Fig. (7.16), and clearly bears no relationship to the observed density/porosity relationships. It can therefore be concluded that, whilst the observed bulk densities do imply the existence of void pore spaces in Tasmanian sandstones, those pores are not the dominating control on the observed effective porosities (water absorptions).

- 2) The theoretical validity of the above function is supported by previous data. Branner (1937, *in* Tickell 1965) found that porosity (p) and density (d) in 82 samples of Palaeozoic sandstones from Arkansas could be related by the function:

$$p = 104 - 40d$$

Similarly, Davis (1954, *in* Tickell 1965) found that 370 sandstone specimens showed the relationship:

$$p = 106 - 40d$$

The average of these two closely similar functions ($p = 105 - 40d$) is plotted on Fig. (7.16), and is very similar to the function $[d = (2.65/100) \times (100-p)]$ which was derived in (1) above from theoretical considerations. It is therefore clear that the densities and porosities of the sandstones studied by Branner and Davis were essentially controlled by their void pore spaces alone.

However, it is again clear that this does not hold true for Tasmanian sandstones, whose bulk density/porosity relationships show no significant relationship to any of the above functions.

If any trend at all exists in the data on Fig. (7.16), it is a very vague trend (dashed line) towards increasing porosities with increasing bulk densities. Since a high clay content in sandstone commonly results in a slightly increased bulk density (Spry 1983,p.60), due to the fact that clays are commonly slightly denser than quartz, this vague trend may reflect an influence of clay content on the observed porosities.

Aside from void pore spaces, the other potential source of porosity (or rather, water absorption) in Tasmanian sandstones is the absorption of water into clay aggregates. Figure (7.17) plots the relationship between effective porosity and total clay content (all clay types) in Tasmanian sandstones. Although it is still a little vague, it is clear that a distinct trend exists, with higher total clay contents being related to higher effective porosities.

Extrapolating the trend backwards, the data suggests that Tasmanian sandstones with zero clay content would theoretically have effective porosities averaging about 3% by volume (range 0 - 7%). Although this situation does not occur, the extrapolation can be interpreted as suggesting that in Tasmanian Permian and Triassic sandstones, whose effective porosities range from approximately 8.5% to 17.5% by vol., between 0% and 7% porosity is a result of void pore spaces, and the (larger) remaining proportion of the porosity is the result of water absorption into clay masses. The dominance of clay content over void pores in determining effective porosity explains the lack of any good correlation between bulk density and effective porosity (Fig. 7.16).

These conclusions are supported by optical and Scanning Electron Microscope observations of Tasmanian sandstones during this project. Under SEM, a small proportion of apparent void interstitial spaces were noted, with pore-linings of delicate, well-formed authigenic clays such as smectite indicating growth into an open space. However, optical thin section examinations showed very few void spaces, other than apparent slide defects caused by the plucking of sand grains during slide preparation. It seems likely that much of the void spaces which do occur in Tasmanian sandstones are of very fine pore diameters.

Of all the common clay types in Tasmanian sandstones, smectite can be expected to absorb the greatest amount of water, since not only do smectite aggregates absorb water into micro-pores or inter-crystalline sites, but in addition the smectite swells by absorption of water into intra-crystalline layers (Gillot 1987). Sandstones with high proportions of smectite could therefore be expected to have higher effective porosities than would be expected for sandstones with similar proportions of other less absorbent clays.

Figures (7.18 & 7.19) plot effective porosity against smectite content for the same sandstone specimens considered in Figures (7.16 & 7.17). As shown by Fig. (7.18) in particular, there is a strong trend towards increasing porosity as the proportion of smectite in the stones total clay matrix increases. While it must be remembered that higher proportions of smectite do in any case tend to be associated with higher total clay contents (see Section 7.8.3), it is also notable that in Figure (7.17), for sandstones of a given total clay content, those with smectite tend to have higher porosities (this trend is indicated because the smectite-bearing sandstones show a strong tendency to plot to the right (higher porosity) side of the line of best fit).

The spread of data points around the line of best fit in Figure (7.17) may be partly explained by variation in the capacity of differing clay types to absorb water, and by variations in the amount of void-space porosity present in particular specimens.

Conclusions

The following conclusions are drawn from the preceding discussions:

- 1) Void pore spaces play a secondary role in determining the effective porosities of Tasmanian Triassic and Permian building sandstones. The sub-ordinate nature of their role is indicated by the lack of correlation between sandstone porosity and bulk density. On the other hand, the fact that void pores are present is indicated by SEM observations, and the fact that the sandstones have a lower bulk density than would be the case if no open pore spaces existed.
- 2) Absorption of water into clay masses is the dominant control on effective porosity (or more accurately, water absorption) in Tasmanian sandstones.
- 3) Although clay masses of all types absorb water, the greatest absorption (and thus the greatest enhancement of effective porosity) occurs in smectite swelling clays.

(B) Controls on the development of porosity in Tasmanian sandstones

The two sources of porosity in Tasmanian sandstones, void pore space and clay content, are considered to be influenced by the following parameters (Tickell 1965, Griffiths 1967, Pettijohn 1975, Leder & Park 1986, Scherer 1987) :

- Grainsize and sorting
- Grain shape
- Grain orientation
- Grain packing
- Degree of compaction
- Detrital quartz content
- Quartz cementation
- Total clay content
- Smectite content
- Micro-fracturing

Most attempts to demonstrate a relationship between porosity and fundamental textural properties such as grainsize, grainshape, etc, have had contradictory results due to interdependences between the various properties (Griffiths 1967,p.230).

Beard & Weyl (1973) and Pettijohn (1975,p.76-77) consider grainsize to have relatively little influence on porosity. Beard & Weyl found that the primary (original) porosity of wet unconsolidated sand is little affected by changes in grainsize for a given degree of sorting, but that porosity increases markedly as sorting improves. Chilingarian & Wolf (1975,p.301) and Pettijohn (1975,p.76-77) attribute this to the fact that, where sand grains differ in size, some may fit inside pores between others and so lower the porosity.

Scherer (1987) found that the primary (pre-compaction and cementation) porosity of wet unconsolidated sand is almost entirely a function of sorting. Scherer's finding assumes a random grain-packing arrangement, which is thought to be the usual situation in nature (Blatt *et al.* 1972, p.71). Theoretically, tight rhombohedral grain packing would produce the lowest porosities, and loose cubic packing the highest (Pettijohn 1977, p.72-73 & 77, Scherer 1987), but variations in size distribution and shapes of particles mean that such regular packing arrangements are not achieved in nature.

Scherer (1987) therefore considered grain sorting to be the dominant variable controlling

primary porosity in wet unconsolidated sands, with other textural characteristics having very little influence except in certain extreme cases (such as strong orientation of dominantly elongated or plate-like grains).

However, Scherer was apparently considering more-or-less clay-free sands; in the light of the earlier discussions, the present writer considers that the detrital clay content of the unconsolidated Tasmanian Permian and Early Triassic sands at the time of deposition must also have been an important control on primary effective porosity. Since poorer sorting will tend to be associated with deposition of greater amounts of water absorbent detrital clays, this is likely to cancel out the decrease in void-space porosity which Beard & Weyl (1973) and Scherer (1987) have shown to accompany poorer sorting.

The present writer therefore considers that the influence on porosity of the textural properties (including the sorting) of the Early Triassic and Permian sands at the time of deposition or early burial cannot be assessed on the basis of present knowledge. However, the relative proportions of detrital quartz and clay in the sands during deposition and early burial are considered to be important to the extent that they influenced the ultimate proportions of clay and quartz in the sandstones subsequent to compaction and diagenesis.

The most important controls on the development of effective porosities in Tasmanian sandstones are considered to have been the following:

Detrital quartz content

Scherer (1987) considers detrital quartz content to be a major control on porosity in uncemented sandstones. Where abundant quartz cementation occurs (as in most Tasmanian building sandstones), porosity is inversely related to detrital quartz plus authigenic quartz cement content. The latter is considered below. Since most Tasmanian building sandstones are dominantly composed of quartz and clay, total quartz content (detrital plus authigenic) can be considered to have an inverse relationship to total clay content (discussed below).

Degree of compaction

Burial compaction of sandstone decreases void-space porosity by pressing sand grains closer together, thereby reducing void interstitial pore spaces (Pettijohn 1975,p.77). The burial compaction of Tasmanian sandstones has been discussed in Section (7.9.1), in connection with the development of welded grain boundaries by pressure solution.

Since compaction is a function of overburden pressure, it can be expected that the greatest degree of compaction (and thus the greatest reduction in porosity due to this cause) will have occurred in the most deeply buried sandstone horizons, which are the Permian and Earliest Triassic horizons. The more compacted sandstones will be characterised by a higher proportion of welded quartz grain boundaries (Section 7.9.1).

Scherer (1987, equation 2) found that porosity in sandstones having only minimal cement did indeed decrease significantly with deeper burial depths. However, Scherer also noted that increasing cementation will stabilise the sandstone framework and so restrain compaction.

It has already been noted above (Section 7.9.1) that the quartz cementation of Tasmanian sandstones is considered to have occurred at shallower burial depths than the major phase of intergranular pressure solution due to compaction. Therefore, while compaction of the sands prior to quartz cementation is likely to have had a significant effect on reducing porosity, continued compaction after cementation would be less important. Since all Tasmanian building sandstones appear to have experienced quartz cementation during deep burial, their post-cementation compaction would have been somewhat restrained (albeit still sufficient to

cause some pressure solution).

This means that the most deeply buried quartz-cemented sandstones would not have been compacted to a very much greater extent than the less deeply-buried horizons. Variations in the degree of cementation during uplift, subsequent to the deepest phases of burial, may have caused greater variations in porosity than any variations in degree of compaction:

Degree of quartz cementation

The precipitation of quartz cement in sandstone pore spaces is considered to be an important process which causes significant reduction in the effective porosity (Leder & Park 1986), both by filling in void pore spaces with quartz cement which may be derived from sources distant from the cemented sandstone body, and also because the production of quartz cement may be related to the breakdown of some of the clay in the sandstone.

Quartz cementation, and variations in the proportion thereof, are discussed in Section (7.9.1).

Total clay content, and smectite content

As demonstrated above, total clay content, and smectite content in particular, appear to be the most important controls on the effective porosity of Tasmanian building sandstones. The lowest possible clay content, and a complete absence of smectite, are preferred so as to achieve the lowest possible porosity. The causes of variation in total clay content, and keys to the location of low-clay sandstones, are discussed in some detail in Sections (7.8.1) and (7.8.3).

No information is available on the prevalence, nature and causes of micro-fracturing in Tasmanian building sandstones.

The development of secondary porosity by leaching of cements (eg, carbonates) is an important process in some sandstones. However, the writer knows of no evidence for significant leaching of carbonate, silica or other cements in the Early Triassic and Permian sandstones under consideration here.

7.10.2 Keys to location of low porosity sandstones

Based on the above discussions, sandstones with the lowest effective porosities (water absorptions) will be those having:

- Lowest void pore space.
- Lowest total clay content.
- Lowest smectite content.

These conditions are most likely to be met in sandstones having the optimum combination of the following properties:

- Well compacted intergranular texture. Lowest stratigraphic horizons (Permian and Earliest Triassic) may have marginally greater degrees of compaction.
- High proportion of quartz cement. It is thought that quartz cement will be most prevalent in sandstones which have experienced higher than average geothermal heatflow subsequent to the major phase of normal burial-related quartz cementation. Tertiary grabens and regions of basaltic intrusions related to mantle hot-spots are

the most likely regions in which this may have occurred.

- Lowest total clay content, and lowest smectite content. In brief, the highest proportions of clay are found in the finer grained sandstones, in smectite-rich sandstones, and probably in sandstones having the highest proportions of relict detrital feldspar and mica.

High proportions of authigenic kaolinite may occur in horizons which have been subject to rapid groundwater flushing, but the locations of such beds are difficult or impossible to predict. Sandstones with a high proportion of ferruginous cement derived by breakdown of vermiculite clay may be relatively low in total clay content (and have the additional advantage of some loss of void pore space due to the ferruginous cementing).

7.11 THE WEATHERING OF NATURAL SANDSTONE OUTCROPS

The preceding sections have described the controls on the various sandstone properties in essentially fresh, unweathered stone. However, relatively intense alteration of sandstone occurs during the final stages of weathering, immediately prior to actual erosion, when sandstone is exposed to the atmosphere in surface outcrops.

An understanding of the alteration processes which occur within a few metres of the surface of natural outcrops is of some importance in building sandstone exploration because:

- 1) Weathering of outcrops affects the amount of information relevant to stone quality that we can determine from natural outcrops, and dictates a need to obtain fresh, unweathered sub-surface samples before we can assess certain critical parameters of potential building stone quality.
- 2) The depth of significant weathering alteration in natural outcrops determines the thickness of low quality weathered sandstone waste which must be removed as overburden in order to extract the fresh, best quality sub-surface stone for building purposes.

During fieldwork associated with the present project, it was commonly noted that natural sandstone outcrops have a case-hardened surface rind (typically 5 - 10mm thick), below which the stone is distinctly soft and porous for a depth of 0.5 m or more. Where adjacent fresh exposures are available, the stone below about 0.5m is generally notably stronger than the surface 0.5m layer.

Data obtained from the Cobbs Hill Quarry (Source 23) provides a typical example (see Appendix One). A sample from a weathered surface outcrop (Cobb 1) yielded an effective porosity of 12.84 vol. % and a dry Point Load Strength Index of 0.64 MPa. In contrast, fresh samples obtained from 0.6 - 3.0 metres below the natural surface in the adjacent quarry pit (samples C/1/1 & C/1/2) yielded porosities of 9.74 - 10.09 Vol. %, and dry Point Load Strength Indices of 4.52 - 6.23 MPa.

However, since the fresh and weathered Cobbs Hill samples were obtained from slightly different stratigraphic heights, it could be argued that the differences in quality could be related to primary lithological differences rather than to weathering effects. It was therefore decided to select a site where weathering alteration effects could be determined from the surface to a depth of some metres in a single sandstone unit of homogeneous lithology.

7.11.1 Weathering alteration in the Elderslie sandstone quarry

A vertical face was excavated at the top of the Elderslie Quarry (Source 26) during July 1989, exposing a homogeneous unit of cross-bedded sandstone from the original natural outcrop surface down to a vertical depth of 3.5 metres (see Plate 7.27). Prior to excavation the outcrop surface was overlain by a soil layer up to 0.5 metre thick. The original outcrop, and the excavated face, have a southerly aspect, so that the face has remained moist since excavation, and is in shade for much of each day.

The entire face exposes a visually identical unit of cross-bedded sandstone of fine grainsize (mean grainsize 0.18 mm diameter) and moderately to moderately-well sorted texture. The stone is a uniform unpatterned yellowish-orange (10 YR 7/6) bulk colour from the surface to depth, apart from a reddish-brown ferruginous rind about 5 - 10mm thick at the original sub-soil outcrop surface. A few clay pellets occur sparsely scattered, and cross-bed laminations have thin micaceous and graphitic coatings throughout the face. There is no



Plate 7.27 Elderslie Quarry, September 1989: view of the upper cross-bedded face. Samples E1 - 11 were taken in a vertical line down the corner. The top of the face is the natural (sub-soil) outcrop surface.

evidence of any primary lithological variation through the full 3.5m depth of the face. Joints are very widely spaced (10 metres +), so that there is little likelihood of increased subsurface alteration due to penetration of water along joints.

In September 1989, eleven samples (E1 - 11) were chipped from carefully measured depths, in a single vertical line running down the face from the natural outcrop surface to 3.5m depth. The relatively small size of the samples obtained by this means precluded strength and porosity testing; however it was considered that careful quantitative measurement of mineralogical and textural properties would serve well as a means of identifying any weathering-related changes in the stone. As argued in preceding sections, these properties are in any case the fundamental controls on strength and porosity.

Each sample was subjected to XRD analysis, and the bulk mineralogy and intergranular texture were measured by microscopic point counting and line traverses of prepared thin sections. The results are presented in Table 7.2 and Figure 7.20.

A number of mineralogical and textural variations occur with depth in the section. Although some of these could be the result of primary variations in the stone, it is highly likely that those variations which show a systematic pattern in relation to the outcrop surface (and which correspond to theoretically predictable surface weathering processes) are in fact the result of surface weathering alteration.

SPECIMEN:	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Depth (metres):	0.0	0.05	0.1	0.3	0.5	1.0	1.5	2.0	2.5	3.0	3.5

MINERALOGY (Vol. % of total mineral matter, by microscopic point count; 300 counts per spec.)

Quartz:	79.0	75.3	72.0	73.3	75.3	78.6	71.6	62.0	67.0	72.0	74.3
Feldspar:	1.0	4.6	1.3	1.6	5.3	2.0	2.6	2.0	2.3	2.6	1.0
Mica:	0.1	0.3	0.6	0.6	<0.3	≈0.1	1.0	0.6	0.6	0.3	0.3
Clay:	9.6	11.3	20.0	20.3	15.3	15.0	20.0	31.0	24.6	21.3	19.3
Fe-oxide (cement)*:	10.3	8.3	6.0	4.0	4.0	4.3	4.6	4.3	5.3	3.6	5.0

* XRD analysis indicates goethite (or limonite) composition

CLAY MINERALOGY (Vol.% of total clay, by quantitative X-Ray Diffraction analysis)

Smectite:	-	-	-	0.5	1	1	1	3	2	<1	0.5
Vermiculite:	26	33	51	61	51	49	40	31	21	39	11
Illite:	68	63	42	36	47	49	59	66	77	60	89
Kaolinite:	6	4	7	3	2	1	-	-	-	-	-

INTERGRANULAR TEXTURE:

INTERGRANULAR BOND TYPES (frequency %, by microscopic line traverse)

Contacts counted:	155	150	154	156	168	154	152	147	151	167	154
Quartz/Quartz:	34	30	21	16	21	27	22	18	20	26	18
Quartz/Clay:	28	42	60	61	57	46	60	68	56	63	54
Quartz/Fe-cement:	35	26	16	21	18	24	11	12	18	9	25
Clay/Fe-cement:	3	2	3	2	4	3	7	2	6	2	3

QUARTZ/CLAY CONTACT TYPES (frequency % of Quartz/Clay category above)

Interstitial clay and pellets:	57	40	30	39	32	22	35	32	37	27	39
Intergranular clay layers and films:	43	60	70	61	68	78	65	68	63	73	61

Table 7.2: Elderslie Quarry Specimens E1 - 11: Mineralogy and intergranular texture data.

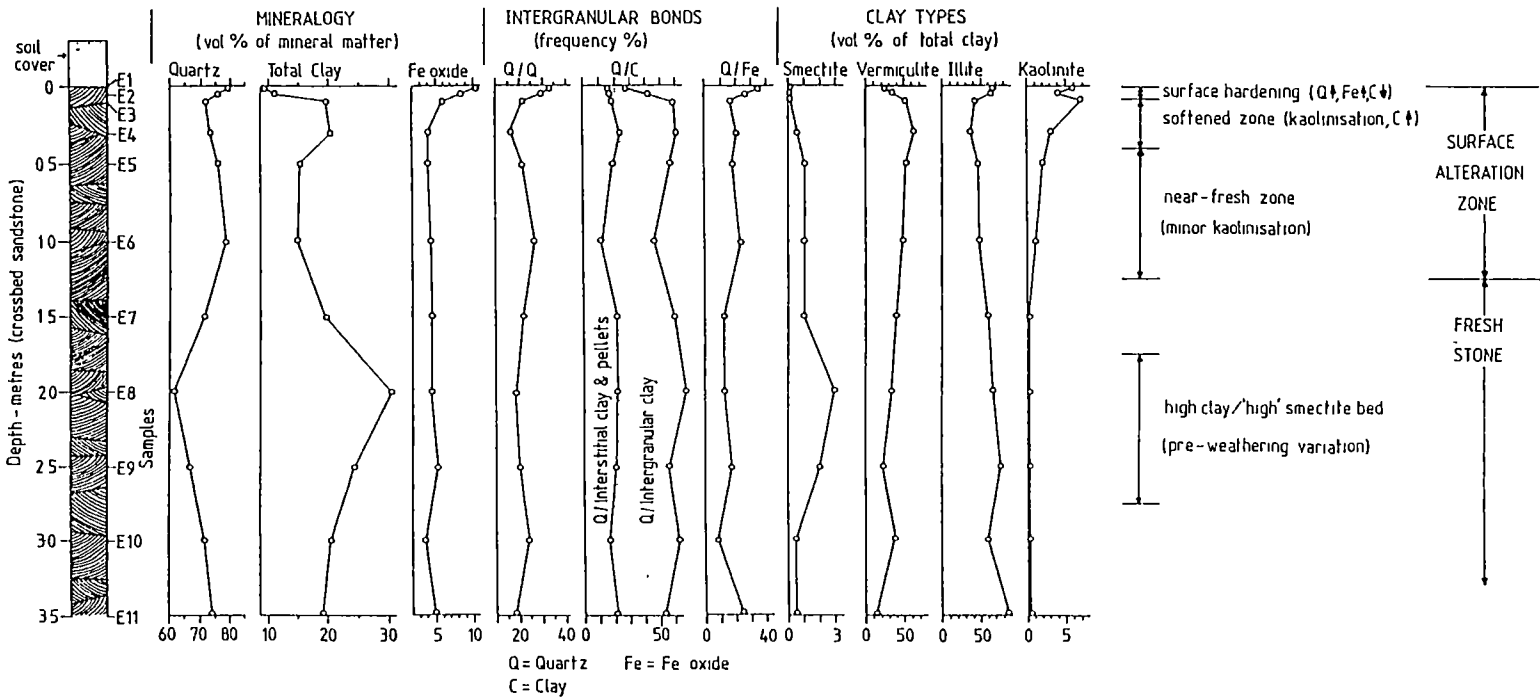


Figure 7.20: Elderslie Quarry: surface outcrop weathering effects as indicated by mineralogical and textural variations. (Data: Table 7.2)

The observed variations are discussed in terms of "alteration zones", from depth to the surface:

1) Fresh zone (below ≈ 1.25 m depth):

The stone below approximately 1.25 metre depth shows no systematic property variations which could be related to surface processes, and is thus considered to represent stone which is unaffected by surface weathering, and whose technical properties could be expected to remain fairly constant to significant depths (assuming continuation of the same lithological type to depth).

A high smectite/high clay/low quartz zone between approximately 1.75 and 2.75 metres depth is considered to represent a layer of primary variation in stone quality, since it shows no apparent systematic relationship to the surface. It is probably a layer having an originally higher content of smectite which, as shown in Section (7.8.3), could be expected to be related to a higher total clay content (and therefore to a lower total quartz content).

This high smectite/high clay bed is therefore an example of the sort of quality variation which can be expected over short distances in fresh stone in most sandstone deposits. It emphasises the need for continuous quality testing of stone for projects where uniform stone quality is important.

2) Near-fresh zone (≈ 0.4 - ≈ 1.25 m depth):

Whereas the fresh stone is free of kaolinite, the onset of weathering is indicated by minor kaolinisation above about 1.25 metres depth. Authigenic formation of kaolinite is a recognised effect of surface weathering, where rapid flushing and leaching by meteoric waters causes feldspars, micas and other clays to alter to kaolinite (see kaolinite discussion in Section 7.8.3).

Other alteration effects are less marked in this zone, although a slight relative decrease in quartz content and frequency of quartz/quartz contacts, together with a slight increase in the frequency of quartz/clay contacts, may be a result of the kaolinisation.

It is likely that technical properties of the stone, such as strength and porosity, are only slightly altered in this zone with respect to the underlying fresh stone.

3) Softened zone (≈ 0.075 - ≈ 0.4 m depth):

Significant kaolinisation is evident in this zone; probably as a result of this kaolinisation, total clay content is significantly increased. The formation of the kaolinite appears to have been mainly at the expense of smectite and feldspar, the latter being significantly depleted in this zone compared to most of the rest of the section (see Table 7.2). However, the occurrence of higher feldspar content in the overlying surface hardening zone is an unexplained anomaly (possibly indicative of a layer which had a higher original feldspar content?).

As a result of the higher clay content, the relative proportions of quartz, and quartz/quartz grain contacts are reduced. This may be due either to actual dissolution of quartz, or (more likely) simply to a reduction in the relative proportion of quartz because of the increase in the absolute proportion of clay.

The higher clay content in this zone probably results in notably higher porosities and lower strength, partly due to replacement of (stronger and less porous) feldspar grains with clay.

In most natural outcrops, it is very difficult to obtain samples from below this zone without

drilling or excavating; hence most samples collected from surface outcrops will come from this weak, porous, clay-enriched zone, and so have properties significantly different to the fresh underlying stone.

4) Hardened surface rind (surface - ≈ 0.075 m depth)

This is the reddened, case-hardened rind which is commonly noted on sandstone outcrops (see Plate 7.6), and which protects natural outcrops from extremely rapid erosion. Total clay content is greatly depleted, probably due both to actual physical removal of soft clay particles by rapidly percolating meteoric waters, as well as to chemical dissolution of smectite and vermiculite (see Fig. 7.11).

A notable increase in ferruginous cement in this zone causes reddening, and is partly responsible for the case-hardening. Much of the iron is probably derived from breakdown of the iron-rich smectite and vermiculite clays associated with kaolinisation in this and the underlying alteration zones; as the resulting Fe-rich waters evaporate at the outcrop surface, the iron is deposited as a ferruginous surface rind (see Section 7.6.4 D).

The proportions of quartz, and of quartz/quartz grain contacts, are also significantly increased in the surface rind. Although this may be partly a relative increase proportional to the leaching of clays, there is probably also an absolute increase due to precipitation of authigenic quartz out of silica-supersaturated meteoric waters evaporating at the outcrop surface (see quartz cement discussion in Section 7.9.1). Some of the silica in the waters is probably derived from the breakdown of the feldspars, micas and clays in the underlying alteration zones.

Although the surface rind is potentially significantly stronger than fresh stone, its thinness means that it has no significance from a building stone point of view.

7.11.2 Potential influences on sandstone outcrop weathering.

The Elderslie section is the only sandstone outcrop whose weathering has been studied in any detail during this project. However, it is considered likely that the degree and type of weathering alteration in sandstone outcrops may vary somewhat in response to a number of factors. These are outlined below, and a more comprehensive testing program proposed which would test the degree of weathering variation that actually occurs.

Factors which are considered likely to influence outcrop weathering include the following:

1) Original mineralogical and textural variations

Sandstones which in their fresh condition are more durable may be less susceptible to alteration than sandstones having poorer characteristics. Thus, a high-quartz, low-clay, low-feldspar, minimally porous (etc) sandstone may experience relatively little alteration, and be altered to shallower depths than sandstones of the opposite characteristics. Such sandstone would consequently erode at a slower rate, and be more likely to outcrop as cliffs or bold exposures.

If this proves to be the case, it would imply that the quality of weathered surface stone could to some extent be correlated with the quality of the underlying fresh stone: better quality weathered stone would imply better quality fresh stone, whereas the occurrence of relatively soft, friable sandstone in weathered outcrops (immediately beneath the surface rind) would imply that the fresh stone would be of relatively low durability.

2) Soil cover

It is probable that rapid and/or extreme fluctuations in temperature and moisture content would accelerate surface weathering processes (and cause them to penetrate to greater depths) for much the same reasons that significant hot/cold and wet/dry cycles can cause pronounced stone decay in buildings (see Chapter Five).

A soil layer overlying a sandstone outcrop would insulate the stone from extremes of temperature variation, and by holding water is likely to keep the underlying stone surface layers relatively moist in all except the most prolonged dry periods.

By reducing the intensity of hot/cold and wet/dry fluctuations in this manner, a soil layer (perhaps even of less than half a metre thickness) is likely to reduce the depth and intensity of weathering alteration in the underlying stone. On the other hand, outcrops which are naturally bare and exposed may be significantly altered to greater depths.

3) Aspect

In Tasmania, outcrops on south-facing slopes spend less time exposed to direct sunlight than do north-facing slopes. This has a similar effect to a soil cover; the south-facing slopes will remain moist for longer, and experience less temperature variation, than north-facing slopes. Therefore, it is likely that sandstone outcrops on south-facing slopes will experience a lesser intensity and depth of weathering than those on north-facing slopes.

4) Vertical versus horizontal penetration of weathering alteration

Much of the weathering alteration noted in the Elderslie outcrop, particularly the kaolinisation, is related to the penetration and flushing through of meteoric groundwater. It is probable that surface water will penetrate a sandstone outcrop further and faster moving vertically down from a horizontal surface than it will moving horizontally in from a vertical face.

Thus, a vertical sandstone cliff with a flat bench at the top could be expected to be significantly altered towards the top, below the bench, but to be less altered going horizontally in from the cliff face below the upper zone of vertical alteration.

A similar effect is well recognised in sandstone buildings (see Chapter Five), where flat vertical walls commonly suffer little decay, but flat ledges, parapet tops, and so forth tend to be the most susceptible to decay.

4) Natural salts

In areas having salty groundwater, precipitation of halite or gypsum in near-surface stone may contribute to stone weakening by causing salt attack. Severe salt attack of this sort is evident on 150 year old faces in Palmers Lookout Road Quarry (Source 2).

A research program to assess the effect of these variables, and to further illuminate the depth and types of weathering alteration to which sandstone outcrops are susceptible, would involve the following:

A range of outcrops of several different general sandstone types would need to be available for sampling and testing. For instance, it would be useful to test a group of outcrops of brown vermiculite-rich sandstones, another group of grey-white sandstones containing similar proportions of only illite and kaolinite clays, and so on. Within each group outcrops should be selected with and without a natural soil cover, and with both southerly and northerly aspects. Widely jointed outcrops should be selected to minimise the alteration effects of water penetration along joints.

At each tested outcrop, it would be necessary to be able to take recently exposed samples at regular intervals from the surface to a depth of at least three or four metres (preferably more). Such samples can only be obtained from either recently excavated faces or cored drill-holes. The necessity of being able to sample in this fashion may make the location of a sufficient number and variety of suitable outcrops difficult, unless money were available to undertake a drilling program for this express purpose.

At each site, it would be necessary to restrict sampling to a single lithological unit having no known primary lithological variations of any significance, so as to eliminate the possibility of confusing weathering alteration patterns with primary lithological variations. Ideally also, at each site two lines of samples would be obtained, one descending vertically from a horizontal outcrop surface, and the other traversing horizontally inwards from fairly low on a vertical natural face.

Sample spacing should be similar to that employed on the Elderslie outcrop (above), and it is considered that the same set of tests would be the most useful in detecting weathering alteration patterns. Where large enough samples are obtainable, additional tests including Ultrasonic Pulse Velocity, porosity and strength would be useful.

7.11.3 Summary: The nature and significance of sandstone outcrop weathering.

If the effects of aspect and soil cover are indeed as postulated in Section (7.11.2) above, then the tested Elderslie outcrop (Section 7.11.1), which has a southerly aspect and was covered by up to half a metre of soil, probably has experienced only a moderate degree of the sort of weathering alteration which can be expected to affect similar vermiculite-rich sandstones in, say, bare natural outcrops with a more northerly aspect. On the other hand, more durable sandstones with a soil cover and southerly aspect may experience even less alteration than the Elderslie stone.

Bearing this in mind, the Elderslie outcrop suggests that the dominant process in the weathering of Tasmanian outcrops is an increase in clay proportions immediately below outcrop surfaces, largely as a result of kaolinisation resulting from alteration and depletion of feldspars, micas and other clay types including smectite. This probably results in a decrease in strength, and an increase in porosity. Similar effects have been recorded at the Cobbs Hill and Buckland quarries, and are suspected to occur in other outcrops, although little suitable data is available on this.

Significant alteration of this sort has occurred to a vertical depth of about 0.4 metre at Elderslie, and minor alteration occurs to over one metre depth. This means that samples obtained by normal (hammer and chisel) surface sampling of this outcrop would not be representative of the quality of fresh subsurface stone, although the mineralogical and textural properties of the surface samples might be vaguely proportional to those of the

fresh stone.

It is noteworthy that smectite is almost or completely depleted in the surface stone at Elderslie; since smectite is commonly found in other surface outcrops this suggests that smectite is only fully depleted at the surface in cases, like Elderslie, where the fresh stone only has relatively small proportions of smectite anyway.

Silica and ferruginous cementation occurs in a thin surface rind. However, no evidence has been obtained to suggest that dissolution of quartz plays a role in the softening of the altered stone immediately below the surface rind.

At Elderslie, the surface 0.4m thickness of stone would be unusable waste in quarrying operations. Fresh stone would be extracted from below 1.25m depth, whilst the intervening slightly altered stone (0.4 - 1.25m depth) should be either discarded as well, or only used in low stress building situations.

7.12 A PROPOSED SANDSTONE EXPLORATION STRATEGY

At the present time there is a demand in Australia for sources of high quality, durable sandstone of uniform texture and uniform (un-patterned) yellow-brown colouration, for use in major restoration and modern building projects. Old sources of such "yellow block" sandstone in the Sydney area and elsewhere have become inaccessible due to urban development and other causes, and no fully satisfactory substitute is yet available.

There is significant potential for the production of such a stone from the uniformly yellow-brown coloured parts of the Tasmanian Lower Triassic Quartz Sandstone Sequence. This thesis provides information and hypotheses as to the geological controls on building sandstone properties. As an example of the potential for applying such information to improve the efficiency of exploration for specific sandstone types of high quality, the following proposal for an exploration program designed to locate sources of high quality "yellow block" sandstone in Tasmania is offered:

7.12.1 An exploration program to locate high quality yellow-brown sandstone in Tasmania.

The Target

The ideal sandstone required will have the following characteristics:

- Uniform, well-sorted texture of fine-medium grainsize, free of textural defects.
- Thick massive bedding.
- Wide joint and fracture spacings.
- Uniform yellow-brown colouration with no (or only very minor) colour bands or other patterning.
- High durability, indicated by high strength, low porosity, strong intergranular texture, low dimensional instability, high quartz content, low total clay content, and an absence of deleterious minerals, particularly smectite.

The only geological unit in Tasmania which contains sandstone with the potential to fit these criteria is the Early Triassic Quartz Sandstone Sequence.

PROCEDURE PROPOSED:

A) Identification of target regions

(1)

Within the total area of Quartz Sandstone Sequence occurrence throughout Tasmania, identify the regions and horizons of highest potential by reference to:

Regional mineralogical and textural variations

- Vermiculite-bearing sandstones are the most likely to provide a uniform aesthetically pleasing yellow-brown bulk colour (Section 7.6.3 B). Two regions of such sandstones are known, in the Linden - Oatlands region and the Blessington region (Section 7.6.3 C, Fig. 7.14). Other similar regions may exist, but have not been identified to date.
- In regard to the Linden-Oatlands vermiculite region, areas towards the southeast should be avoided due to the likelihood of high smectite (and thus high total clay) contents. The vermiculite sandstones furthest away from the southeast of Tasmania are the least likely to contain smectite (Section 7.8.3).

- Although the western and northwestern margins of the Tasmania basin must be avoided due to the likelihood of excessively coarse grainsize and excessive quartz pebble content, on the basis of present knowledge all other areas of the basin are equally prospective for fine- to medium-grained sandstones in thick massive beds (Chapter 3, sections 7.5, 7.7.1).
- Areas which have experienced higher than average heatflow are likely to be strongest and least porous due to a high proportion of quartz cement (Section 7.9.1). Such areas may include Tertiary Grabens, but these may be unsuitable due to also being closely jointed (see below). Possible high potential areas outside the grabens are those which have moved over hot-spots associated with Tertiary basalt intrusions.

Stratigraphy

- The upper parts of the Quartz Sandstone Sequence are likely to have low prospectivity, since they may be excessively fine grained and thinly bedded (Sections 7.7.1 & 7.5.2), excessively feldspathic and micaceous (Sections 7.8.2 & 7.8.5) and thus likely to have high total clay contents (Section 7.8.3).
- Lowest few metres of the Sequence likely to be too coarse and pebbly (Sections 3.3.2, 7.5, 7.7.1). However, above that:
- The lower portions of the Quartz Sandstone Sequence probably have a greater prevalence of brown vermiculite sandstones (Sections 7.6.3 C & 7.8.3), more abundant thick massive beds than the upper parts (Sections 3.3.2, 7.5.4), and may have slightly increased strength and reduced porosity due to being more compacted and having more welded quartz grain boundaries (Sections 7.9.1 & 7.10).

Therefore the lower parts are more prospective (eg, RIs in the Hobart/Brighton region, lower half of Rp in the Midlands region, etc). However in many parts of Tasmania the Quartz Sandstone Sequence has not been differentiated on a mapping scale, so that this exploration key cannot be used to narrow down such regions prior to fieldwork.

Fault and jointing densities

- Target regions of low Mesozoic to Tertiary fault density. As indicated in Fig. 7.2, particular areas of high fault density to be avoided are the Tertiary horst and graben structures, and the increasing mid-Mesozoic fault density towards southern Tasmania (see Section 7.4).
- Prior to serious fieldwork a more detailed version of Fig. 7.2 should be prepared to better indicate low fault-density areas by the means described in Section (7.4.2 [2]).

Any relevant data from previous sandstone exploration.

A useful map could be prepared, showing all areas of Quartz Sandstone Sequence outcrop, and indicating all the available regional data outlined above, so as to indicate the regions of high and low potential throughout the state.

(2)

List resulting high-potential target regions (eliminating any which will be unsuitable by reason of In-adequate access, environment, land tenure or other practical reasons).

B) Field Reconnaissance

For all prospective regions, systematically reconnoitre one at a time, in as much detail as possible, by road and foot.

(1)

There are few exploration keys available to predict prospective local sites within a particular region, other than simply to examine as many outcrops as possible in the field. Such local exploration keys as might have some value include:

- Use of airphotos prior to fieldwork to locate areas of widespread or bold outcrop (likely to indicate widely spaced jointing and thick-bedding - see Sections 7.4.2 & 7.5.4).
- It is not necessary to avoid the immediate vicinity of major faults in order to locate widely jointed outcrops. Since it appears to be the regional fault density which is related to joint density (section 7.4), the occurrence of an individual fault in a region of generally low fault density need not produce increased jointing density other than within a few metres of the fault.
- Within any region, the lower part of the Quartz Sandstone Sequence is likely to be more prospective than the upper part (see above). Further, within individual (eg, outcrop-scale) depositional cycles, thick massive beds of fine- to medium grainsize are more likely to occur low in the cycle (Sections 7.5, 7.7.1).

Note that quartz pebbles and clay pellets are most likely to occur at the very base of each cycle (Section 7.7.1). The upper parts of individual cycles are likely to be excessively fine-grained and thinly bedded (Sections 7.5 & 7.7.1).

However, prediction of exactly where in a particular local area massive beds may occur, by observation of the pattern of local bedding successions, will rarely be feasible due to unpredictable truncations and variations of the "ideal" bedding sequences.

- Avoid sandstone areas within 500 metres of intrusive dolerite contacts, as such areas are likely to have significant Liesegang rings and other ferruginous colour patterning (Section 7.6.4). However, sandstone within 500 metres of faulted dolerite contacts may not have such colour patterning, and so are worth examining for uniform-coloured stone.
- South-facing and/or permanently shaded slopes and/or outcrops with a thin soil cover at the top of outcropping faces are likely to have suffered less weathering-related alteration and weakening of the surface layers of stone.

(2)

Locate sites having:

- Thick massively bedded horizons of uniformly-coloured yellow-brown sandstone, having uniformly-textured well-sorted fine-medium grainsize, and free of defects such as ferruginous nodules, clay bands, quartz pebbles, clay pellets. Note that fresh colour and colour patterning is sometimes difficult to determine on weathered outcrops, due to surface discolouration extending some centimetres into the outcrops.
- Wide joint and fracture spacings, low-angled bedding dip.
- Natural outcrops having superficial polygonal ("Pachydermal") fracturing should be treated with caution, since the pachydermal fracturing may be an indication of an undesirably high degree of dimensional instability related to an intergranular texture dominated by weak intergranular clay bonds (see Sections 5.4.2 & 7.9).
- Fine-to-medium grained sandstones, rather than fine-grained sandstones, are likely to have lower clay contents and are therefore probably preferable.
- Suitable access and site topography for economic quarry development.
- Minimal (1-2m max.) overburden of soil and unsuitable sandstone types.
- Minimal environmental problems.

For maximum efficiency in the field, do not bother recording data on sites which do not fit above criteria. There are few possibilities for using detailed information on unprospective outcrops to help lead to good quality outcrops nearby (see (1) above); such detailed data-recording could become a time-wasting inefficiency in this type of exploration.

Rather, simply keep a record of which target regions have been examined (and in how much detail), and record detailed data only on those sites which are judged to be prospective and worthy of further testing. Do, however, record the broad characteristics of the sandstones in each prospective region, since such data may be of value in detecting broad-scale trends in sandstone types and characteristics throughout the state.

(3)

Ideally, end up with a list of ten or more prospective sites fitting the above criteria.

C) Preliminary testing

(1)

Collect the freshest obtainable samples (2-3 per site) from each prospective site.

(2)

Subject each sample to XRD analysis and thin section microscopy to determine:

- Clay types present, including presence or absence of smectite.
- Quartz, feldspar, mica and clay proportions (Point count).
- Intergranular texture (Line traverse).

(Strength and porosity testing of outcrop samples is probably of little value since weathering alteration may significantly affect these parameters.)

Eliminate sites having significant smectite or very weak intergranular texture. Since intergranular texture may also be somewhat affected by weathering in outcrop samples, do not immediately reject sites having "borderline-quality" intergranular textures.

D) Evaluation

(1)

Show all remaining prospective sites to experienced quarryman. Eliminate any he considers to be definitely unsuitable.

(2)

Approach landowners of remaining prospective sites to determine their attitude to possible quarrying operations. Rank remaining prospects in order of their potential with respect to:

- Field characteristics.
- Preliminary laboratory results.
- Quarryman's assessment.
- Landowner's co-operativeness.

(3)

For the 2 or 3 top-ranking prospects, obtain fresh sub-surface samples (from at least 2 metres below natural surface) by means of (preferably) drilling, or by excavation. For sites not currently accessible to heavy drill-rigs, the use of a light backpack-carried core-drill may be considered (due to the likely expense and possible environmental damage, it may be better to defer construction of good-quality access tracks until a prospect appears certain to be worth developing as a quarry).

Ideally, a grid of several holes should be drilled at each prospect, in order to allow early assessment of sandstone type and quality variation through the deposits, and to allow calculation of reserves. If budgeting does not allow this, one drill-hole at each prospect may suffice at this stage, but should be followed by grid drilling at the final chosen quarry site before large-scale quarrying commences.

(4)

Subject fresh sub-surface samples to a full set of tests, including as a minimum:

- Ultrasonic Pulse Velocity
- Mineralogy & intergranular texture (by thin section microscopy)
- Clay mineralogy (by X-Ray Diffraction analysis)
- Effective porosity, water absorption, dry bulk density
- Point Load Strength Index (wet, air-dried, oven-dried, parallel & perpendicular to bedding)

The following tests are also worthwhile if feasible or considered appropriate:

- Compressive Strength (as for Point Load Test)
- Flexural Strength
- Dimensional Instability
- Abrasion Resistance
- Sodium Sulphate Soundness Test

Eliminate prospects which do not conform to the required standards in terms of these test results and/or in terms of the stratigraphy or defects revealed by drilling.

If no sites meet the required standards, re-assess lower-ranked prospects, or re-assess prospective regions and conduct further field reconnaissance exploration.

(5)

For sites which meet required standards after drilling and lab testing, obtain fresh blocks by excavation. Submit to an independent stone testing laboratory such as AMDEL (Adelaide) for full suite of tests to obtain another opinion.

(6)

Select the most favourable site for quarry development. If possible, further drilling should be conducted to enable quarry development to be planned in the most efficient possible fashion.

CHAPTER EIGHT

CONCLUSIONS

8.1 INTRODUCTION

A significant amount of previous work, both in Tasmania and elsewhere, has led to a reasonable understanding of the causes of sandstone decay in the built environment, and it is possible to identify the sandstone properties controlling susceptibility to decay (see Sections 1.3, 6.2 and Chapter 5). In addition, it is a simple matter to list sandstone properties which, while not directly related to durability, are nonetheless important factors determining the quality of stone for building purposes (eg, jointing and colouration).

However, while the nature of those sandstone properties which determine quality and durability are at least partly understood, little work has been undertaken to relate those properties to the geological processes which produced them. Such an understanding is necessary to facilitate more efficient approaches to exploration for deposits of high quality building sandstone.

The most important part of the work in this thesis (Chapter Seven) constitutes a first attempt at a comprehensive study of the geological processes determining the quality of Tasmanian building sandstones.

The most important contribution made by this thesis is not that any firm conclusions have been reached, but rather that the major problems requiring study have been defined.

8.2 SUMMARY OF RESULTS

The conclusions (most of which are only tentative) reached in this thesis can be summarised in terms of the three aims presented in the introduction (Section 1.6):

Aim 1

To ascertain which tests or measured stone properties can most reliably indicate the durability of Tasmanian sandstones in the built environment.

Three approaches to assessing sandstone durability are considered:

- 1) Direct measurement of sandstone properties considered to govern resistance to decay.
- 2) Accelerated decay testing.
- 3) Observed decay in buildings.

Each method is subject to limitations; optimum assessments are made by interpreting a combination of data from all three approaches, in the light of an understanding of the nature of sandstone properties and of the processes of sandstone decay.

In addition to macroscopic criteria such as jointing, bedding and grainsize, the sandstone properties which ultimately control durability are considered to be:

- Mineralogy (percentage of various minerals present, including particular clay types).
- Intergranular texture.

Other important properties, which are largely a function of the above fundamental properties, include:

- Strength (compressive, tensile, flexural, modulus of reupture).
- Porosity (effective porosity, water absorption, bulk density).
- Dimensional Instability.
- Ultrasonic Pulse Velocity
- Other properties, such as abrasion resistance, may be important in particular applications.

Accelerated decay tests (eg, sodium sulphate or sodium chloride cyclic salt crystallisation tests) give results which show a significant relationship to stone strength and porosity, and have been shown to be a fairly good indicator of sandstone decay in response to salt attack. However, accelerated decay testing alone does not give a good prediction of stone decay in response to processes such as clay swelling, and therefore predictions of sandstone durability must not rely upon accelerated decay test results alone.

Observed decay of sandstone in the actual building environment is in some respects the most reliable means of assessing sandstone durability. However this method is inapplicable to stone from previously unused sources, and moreover provides only a fairly subjective durability assessment. Sandstone used in a different environment, subject to different stresses, from that in which it has previously been observed in existing buildings, will not necessarily perform in the same way.

Aim 2

To provide an inventory of the major historical and modern sources of building stone in Tasmania, incorporating data on stone properties influencing durability.

This aim was initially considered to have been achieved, and the data obtained is presented in Chapter Four and Appendix One. However, as the work on Aim (1) above progressed, it became apparent that the significance of some important fundamental properties had not been recognised during the initial phase of data collection, so that the data base compiled can now be seen to be deficient in some important respects (although the original data is still valid and useful).

Circumstances have not permitted a comprehensive re-sampling and re-testing of all sandstone sources in order to correct the deficiencies in the data-base. Such a program of re testing is proposed in Chapter Nine.

In respect of Aim (2), the major contribution of the work in this thesis has been the recognition of which sandstone properties should be determined in any future work.

Aim 3

To investigate the influence of depositional, diagenetic, tectonic and weathering environments in producing those sandstone properties which govern quality and durability.

The tentative conclusions reached include the following:

- On the basis of current knowledge, the fluvial sandstones of the Permian Lower Freshwater Sequence and the Early Triassic Quartz Sandstone Sequence are the only Tasmanian geological units likely to provide good quality building sandstones.
- The jointing in these sandstone units is largely related to Mid-Mesozoic and Tertiary faulting. The regions most prospective for widely-jointed sandstone can be predicted on the basis of known regional variations in fault densities.
- For most building purposes, thick massive bedding is the ideal. Such bedding is most prevalent in the lower part of the Quartz Sandstone Sequence, and towards the base of individual depositional cycles. There appears to be little potential for predicting the prevalence of such beds in terms of regional (lateral) variations over most of the depositional basin.
- The colour of sandstone is related to the content of iron-rich minerals. A uniform brown bulk colour is most commonly produced by ferruginous cements derived from the oxidation of vermiculite clay (oxidation of chlorite and smectite may have a similar effect in some instances). Sandstones free of vermiculite, chlorite or smectite most commonly have a uniform grey-white bulk colour. The vermiculite is considered to have a volcanic origin, and shows a well defined regional distribution pattern, possibly with some stratigraphic control as well.

Brown liesegang ring patterns form through groundwater processes in proximity to intrusive contacts with iron-rich basic intrusions, most commonly Jurassic dolerite.

- Textural and clastic mineral characteristics show some tendency to vary systematically going stratigraphically up through the Quartz Sandstone Sequence, with the most durable sandstones occurring in the lower parts. However, apart from the occurrence of very coarse beds near the western and northwestern margins of the Tasmania Basin, no systematic lateral variation in these properties has been recognised.
- The occurrence of the detrimental swelling clay smectite varies markedly within individual outcrop areas, but on a larger scale there appear to be well-defined regional patterns to its occurrence, and there may also exist some stratigraphic control. The origin of the smectite is considered to be related to contemporaneous volcanic activity, and its distribution shows a relationship to that of vermiculite.
- The clays in Tasmanian building sandstones are both detrital and authigenic in origin. The highest clay contents occur in the more fine-grained sandstones, in micaceous and feldspathic sandstones, smectite-bearing sandstones, and sandstones which have undergone significant kaolinisation due to rapid groundwater flushing during uplift.
- The most important controls on the strength and dimensional stability of Tasmanian building sandstones are the relative proportions and types of intergranular quartz and clay bonds. These properties can be related to patterns of quartz and clay abundance,

and to processes of burial and diagenesis.

Pachydermal weathering fractures on natural outcrops are considered to be an indicator of dimensional instability.

- The porosity (or water absorption) of Tasmanian building sandstones is primarily a function of water absorption into clay aggregates, with void interstitial pore spaces being of secondary importance. Porosity is related to total clay content, total smectite content, compaction and quartz cementation (all of which are also controls on sandstone strength).
- The weathering of natural sandstone outcrops causes significant alteration of sandstone properties within a metre or so of the surface, primarily as a result of kaolinisation. This places important limitations on sandstone exploration procedures, and is of significance in quarrying operations.

CHAPTER NINE

FURTHER WORK

9.1 INTRODUCTION

The various lines of research whose importance have become apparent during this project are too wide ranging to have all been properly followed through to a conclusion within the scope of this thesis. For reference, this chapter presents a brief listing of proposed lines of investigation, with references to the sections of this thesis in which their importance is discussed, and methods of investigation proposed.

Many of these lines of research will lead to conclusions having relevance beyond the field of building sandstone research. For instance, investigation of the distribution and genesis of smectite and vermiculite clays in the Quartz Sandstone Sequence of Tasmania is likely to lead to significant conclusions relating to Early Triassic palaeogeography and vulcanism.

9.2 PROPOSED FUTURE WORK

1) Compilation of a comprehensive technical data base

One of the initial aims of this project was to compile a comprehensive data base on the durability-related technical properties of Tasmanian building sandstone sources. This was one of the first research aims achieved during this project, and the results are presented in Chapter Four and Appendix One.

Unfortunately, as the work progressed, it became apparent that this initial data base was subject to severe limitations. Many of the samples tested (particularly those from old buildings and historic quarries) were somewhat weathered and therefore gave results which cannot be considered indicative of the quality of the fresh stone. Furthermore, it became apparent that a number of properties (eg, intergranular texture) which were not measured during the initial data-collecting are in fact very important controls on sandstone durability.

In the latter stages of this project it was not possible to comprehensively re-sample all the sandstone sources, and to subject fresh samples to a full set of the tests and determinations which were by then considered to be important.

It is therefore strongly recommended that fresh samples be obtained from at least all the currently operating quarries, and preferably also the major historic ones, and that these be simultaneously subjected to a full set of the tests and determinations outlined in Chapter Two and Appendix Three. This will allow a more confident assessment and comparison of the durability of the various sandstones available in Tasmania to be made.

2) Improved assessment of the relationship between accelerated decay test results and sandstone properties and decay

A research program of this nature was carried out during this project (see Section 6.3.1), but has subsequently been seen to be subject to a number of deficiencies. An outline of an improved research program which eliminates many of the deficiencies is given at the end of Section (6.3.1).

3) Quantification of the relationship between sandstone properties and modes of stone decay in buildings

It would be very useful to be able relate the fundamental properties of a sandstone to the type and degree of decay it can be expected to suffer in a building. At present it is only possible to do this in a rather general qualitative way.

Achieving the ability to quantitatively or semi-quantitatively predict sandstone decay in this way would require a very large body of data, and a complex multi-variate analysis. Nonetheless, an outline of the manner in which such research could be conducted is provided in Section (6.4.1).

4) Jointing investigation

The spacing of joints and fractures in a sandstone deposit is a very important parameter, since it determines the maximum size of unflawed blocks which can be removed from a quarry, and is also a major determinant of the wastage experienced in quarrying operations.

Work to date (Section 7.4) indicates that the most important cause of jointing in Tasmanian sandstones is tectonic stress, and that the average joint spacing varies between geographical regions of Tasmania, in a manner which can be related to the tectonic events responsible.

The understanding of the relationship between tectonic events, faulting and jointing is still somewhat sketchy. Section (7.4.2) outlines a proposed program of research designed to:

- a) Quantitatively determine whether a predictable relationship exists between the density of mapped faults and the density of outcrop-scale jointing in a given region.
- b) Determine the degree of variation in regional fault densities throughout the Tasmania Basin. By application of the results from (a) above, this would hopefully lead to preparation of a map indicating expected average joint densities through the Tasmania Basin, which in turn would become a valuable tool in sandstone exploration, by indicating the areas most likely to contain widely jointed sandstones.

5) The genesis, distribution and significance of smectite, vermiculite and chlorite in the Quartz Sandstone Sequence

Smectite is a particularly deleterious clay whose presence has important implications for building sandstone durability (Section 5.3.9). The presence of the iron-rich clay vermiculite has been implicated in the production of a uniform brown bulk colouration in sandstones of the Early Triassic Quartz Sandstone Sequence (Section 7.6.3 B), and smectite may also play a role in brown bulk colour production. The presence of iron-rich chlorite appears to produce a similar colouration, but apparently only within a few metres of weathered outcrop surfaces.

On the basis of the sparse data currently available, there appears to be a geographical and possibly a stratigraphic control on the occurrence of smectite and vermiculite-rich sandstones (Section 7.6.3 C, 7.8.3).

The genesis of the smectite and vermiculite may be related to Triassic volcanism (Section 7.8.3).

The following lines of research are considered worthwhile:

- a) Further petrographic, mineralogical and chemical study of the smectites and vermiculites in the Quartz Sandstone Sequence is urged, with a view to establishing the origin of the clays (Vulcanism? Type of vulcanism? Mode of deposition, eg, from volcanic dust clouds?). Evidence for the nature of the clay parent minerals should be looked for (relict volcanic glass and other materials). See Section (7.8.3).
- b) A large number of random samples of Quartz Sandstone Sequence sandstones should be collected from all accessible areas of the Tasmania Basin. Sandstones of all colouration types should be sampled, and the bulk colour of each recorded. The only exception is that outcrops with strong liesegang ring colour patterning should be ignored, as the processes responsible for the ring patterning may also have affected the bulk colour of the stone. The stratigraphic position of each sampled site should be recorded, insofar as this can be determined.

Each sample should be subjected to a detailed XRD analysis, sufficient to differentiate between any chlorite or vermiculite which may be present. With the data so obtained, it will be possible to refute, or confirm and expand upon, the preliminary conclusions drawn in Sections 7.6.3(B & C) and 7.8.3 of this thesis. Specifically:

- To determine whether vermiculite is indeed a significant component of sandstones having a brown bulk colour, and is minor or absent in sandstones of grey/white bulk colour. Further, to determine whether chlorite is also a significant component of sandstones having a brown bulk colour to significant depths below outcrop surfaces, or whether (as is suspected) chlorite-rich sandstones only develop a brown bulk colour within a few metres of outcrop surfaces. Also to determine whether any relationship between smectite content and bulk colour exists.
- The geographical distribution of smectite and vermiculite-rich (and chlorite-rich?) sandstones should be mapped. If the data allows, it should also be determined whether there is any stratigraphic control on the occurrence of these clays in the Quartz Sandstone Sequence.

Not only will this information provide a useful guide to the areas (and stratigraphic horizons) in which smectite-free, and brown or grey-white sandstones can most profitably be explored for, but it may also provide valuable palaeogeographical (and stratigraphic?) data on the spatial and temporal distribution of the geological processes (vulcanism?) responsible for the deposition of the smectite, vermiculite and chlorite. From the latter point of view, it might be useful to extend a similar research program to the entire sequence of Parmeener Supergroup rocks.

The data so obtained should also facilitate testing of the hypothesis (Section 7.8.3) that vermiculite and smectite formed from different mineral fractions of the postulated volcanic ash clouds, and that the differing fractions were transported different distances. An estimate of the number, direction and distances to the postulated volcanic centres may be possible.

- c) If fully cored drill-holes collared in smectite, vermiculite or chlorite-rich sandstones of the Quartz Sandstone Sequence are available, it would be useful to carefully log colour changes throughout the holes, and to take regularly spaced samples for XRD analysis from the entire drilled depth of the Sequence.

This would allow determination of any stratigraphic patterns which may exist in the distribution of the smectite, vermiculite and chlorite, and would also allow confirmation of the hypothesis (Section 7.6.3 B) that the presence of vermiculite produces a brown colouration to the depth of the zone of oxidising groundwater circulation, and that a grey/white colouration is prevalent in vermiculite sandstones at greater depths.

6) The processes of Liesegang-ring formation

It is likely that Liesegang Rings form as a result of near-surface precipitation of ferruginous minerals leached from adjacent mafic igneous rocks, and transported into sandstones by groundwater flow (Section 7.6.4 A, B & C). Although the evidence points to such a late-stage process (as opposed to liesegang ring formation contemporaneously with mafic igneous intrusion), the hypothesis has not been specifically confirmed.

Several tests are proposed in Section (7.6.4 C) which can refute or confirm the hypothesis. It is recommended that one or more of these tests be conducted in rigorous detail.

7) Stratigraphic and lateral (regional) mineralogical, textural and bedding thickness variations in the Tasmania Basin

Current evidence suggests little or no gradient across the Tasmania Basin in regard to average grainsize, sorting, bed thickness or lutite content, although there is a suggestion of decreasing grainsize and bed thickness, and increasing clay, feldspar and mica content going stratigraphically up through the sequence (Sections 3.3.2, 7.5.2, 7.7.1). In general, more distal areas are expected to have finer grainsize, more lutite, and thinner bedding. Since this has not been observed, it suggests that the currently exposed basin is a small part of an originally much larger basin.

Determination of whether there is or is not in fact such a gradient across the basin could be achieved by the selection of a number of cored drillholes through the Quartz Sandstone Sequence in proximal, distal and intermediate areas of the basin. In each, carefully measure mineral contents, grain sizes, sorting, bedding thicknesses and lutite contents (both as proportion of lutite beds, and clay % in sandstones) throughout the drilled thickness of the Sequence. Statistically determine whether there are any significant stratigraphic trends in each of these parameters through individual drill-holes, and compare each drillhole to determine whether any gradients can be discerned across the basin.

This has significance in exploration, as it will indicate whether or not there are areas of the basin, and particular stratigraphic levels, in which better mineralogies, intergranular textures and bedding thicknesses can be expected to be more prevalent.

A research program of this sort would also provide data for the study of smectite, vermiculite and chlorite clays outlined above.

8) Significance and genesis of intergranular textures

Intergranular texture (Section 2.3.4), along with the related properties of total quartz and clay contents, is considered to be the fundamental control on sandstone strength, porosity and dimensional stability (Sections 7.9 & 7.10).

Investigation of the significance and genesis of these properties is important from the point of view of sandstone exploration. Investigations should include:

- Comparison of quantitative measurements of intergranular texture parameters (Section 2.3.4 & A 3.2.3) with measured strengths, porosities, dimensional stabilities, etc, to determine the degree to which the latter properties can be predicted from intergranular texture.
- Investigation of any patterns in variations of degree of sandstone compaction and proportion of welded boundaries (more prevalent in lower horizons?). See Sections (7.9.1) & (7.10.1).
- Determination of any regional or stratigraphic variations in proportions of quartz cement (Sections 7.9.1 & 7.10.1). In particular, determination of whether any relationship between high quartz cement content and high geothermal heatflow regions can be perceived.
- Investigations of the causes of high and low total clay contents (Section 7.8.3), including investigation of the relationship between grain size, bedform type and clay content (Section 7.8.1). Investigation of the causes of the production of intergranular clay layers and films (Section 7.9.1).

9) Weathering of natural sandstone outcrops

It has been established (Section 7.11) that significant alteration of sandstone properties may occur within a metre or so of weathered sandstone outcrop surfaces. This has important implications for both sandstone exploration and the development of quarries.

However, the degree of variation in the type and intensity of weathering which may occur under various circumstances has not been determined. A program of research to do so is outlined in Section (7.11.2).

In conjunction, further investigation of the significance of superficial pachydermal fracturing (Section 7.9.3) may provide a very useful exploration tool for the identification of sandstones having poor intergranular textures and a high degree of dimensional instability.

9.3 A STANDARD DATA RECORDING FORMAT

Several of the proposed research programs outlined in Section (9.2) above require data from a widely distributed set of sandstone outcrops throughout the Tasmania Basin. This applies particularly to investigations of jointing, clay type distribution, textural variations, and intergranular texture variations. The existing data base has allowed some preliminary conclusions to be drawn, but most of these will not be conclusive until a better distribution of data points is obtained.

In order to facilitate these proposed research programs, it is proposed that the following set of observations and tests be conducted on all Early Triassic Quartz Sandstone Sequence

sandstone outcrops examined in any detail in future (regardless of the immediate purpose of examining the outcrop):

In the field:

- Record:
- Site number, location, grid reference.
 - Aspect of outcrop, whether naturally bare or soil covered.
 - Stratigraphic height, insofar as can be determined; note means of determination (eg, by correlation with significant horizons, simple height in metres from top or bottom of local Sequence, etc) and degree of uncertainty.
 - Distance and direction to nearest dolerite or basalt intrusion, nature of contact.
 - Distance and direction to nearest fault(s). Strike and size of the fault (s).
 - Joint spacing, number of joint sets, strike & dip of each.
 - Bedding: dip, type(s), thickness(es).
 - Grainsize
 - Bulk colour
 - Colour patterning: type, intensity.

- Samples:- 1 - 2 per site.
- Record location, beds from which taken.
 - Record freshness (vertical and horizontal distance from natural outcrop surfaces).

Laboratory tests on each sample:

- Minimum:
- Petrography: Mineralogy (by Point counting). Min 300 counts.
Intergranular texture (by line traverse). Min. 150 contacts.
 - Clay Mineralogy (by XRD); differentiate chlorite and vermiculite whenever present.

- If possible:-
- Effective porosity/water absorption/dry bulk density
 - Point Load Strength Index (wet, air dry, oven dry, normal and parallel to bedding).
 - Additional petrography: determination of relative proportions of welded and cemented quartz/quartz grain bonds.
 - Other standard tests.

REFERENCES

- Aguilera, A., 1988: Determination of subsurface distance between vertical parallel natural fractures based on core data. A.A.P.G. Bulletin, v.72, No.7 (July 1988), p.845 - 851
- Allen, J.R.L., 1968: Current Ripples. North-Holland Publ. Co., Amsterdam, 433p.
- Allen, J.R.L., 1982: Sedimentary Structures, their character and physical basis, Vol.II. Elsevier, Amsterdam, 663p.
- American Society for Testing and Materials, 1984: 1984 Annual Book of ASTM Standards - Volume 04.08 Soil and Rock; Building Stones. A.S.T.M., Philadelphia, 830pp.
- Amoroso, G.G., and Fassina, V., 1983: Stone Decay and Conservation. Materials Science Monographs, No.11, Elsevier, Amsterdam, 453p.
- Anon., 1964: Priceless Heritage - Historic Buildings of Tasmania. Platypus Publications, Hobart, Tas.
- Anon., 1975: Specification Technical Study 1: Testing porous building stone. The Architects Journal, 13 Aug. 1975, p.337-339 (Great Britain).
- Arditto, P.A., 1983: Mineral-groundwater interactions and the formation of authigenic kaolinite within the southeastern intake beds of the Great Australian (Artesian) Basin, New South Wales, Australia. Sedimentary Geology, v.35, p.249-261.
- Bacon, C.A., & Everard, J.L., 1981: Pyroclastics in the Upper Parmeener Supergroup near Bicheno, eastern Tasmania. Pap. Proc. Roy. Tasm., v.115, p.29-36.
- Baker, R.T., 1915: Building and Ornamental Stones of Australia. Technological Museum, Sydney: Technical Education Series, No. 19.
- Banks, M.R., 1972: Report on Thickly Bedded Sandstone. Unpubl Rept. for Etna Stone Pty. Ltd., 16th June 1972, Hobart, Tasmania.
- Banks, M.R., 1973: General Geology. In: Banks, M.R., (Ed.), The Lake Country of Tasmania. Roy. Soc. Tasm., Hobart, P. 25 - 34.
- Banks, M.R., & Naqvi, I.H., 1967: Some formations close to the Permo-Triassic boundary in Tasmania. Pap. Proc. Roy. Soc. Tasm., v.101, p.17-30.
- Beard, D.C., & Weyl, P.K., 1973: Influence of texture on porosity and permeability of unconsolidated sand. A.A.P.G. Bull., v.57, p.349 - 369.
- Beattie, J.W., (date uncertain; post-1901): Handwritten list of sandstone sources for Hobart Buildings. Beattie Manuscript File, Allport Library, State Library of Tasmania, Hobart.

- Bell, F.G., 1983: Fundamentals of Engineering Geology. Butterworth & Co., U.K.
- Belousov, V.V., 1962: Basic Problems in Geotectonics. McGraw-Hill Inc., 809p.
- Berkman, D.A., and Ryall, W.R. (Eds), 1976: Field Geologists Manual. Monograph Series No.9, Aust. Inst. Min. Metallurgy.
- Berry, R.F., and Banks, M.R., 1985: Striations on Minor Faults and the Structure of the Parmeener Super-Group near Hobart, Tasmania. Pap. Proc. Roy. Soc. Tasm., v. 119, p.23-29.
- Berry, L.G., and Mason, B., 1959: Mineralogy: Concepts, Descriptions, Determinations. W.H.Freeman & Co., San Francisco, 630p.
- Bieniawski, Z.T., and Franklin, J.A., 1972: Suggested method for determining the Point Load Strength Index. Part 2, Committee on Laboratory Tests Document No.1, Final Draft Oct.1972, International Society for RockMechanics.
- Bieniawski, Z.T., 1975: The Point Load Test in geotechnical practice. Eng. Geol., v.9, p.1-11.
- Blake, F., 1958: Buckland. 1 mile series, Geological Atlas, Geol. Surv., Tas. Dept. Mines.
- Blake, F., 1958a: Tyndall's Paving Stone, Kingston. Tech. Reps. Dept. Mines Tasm., No.2, p.72-73
- Blake, F., 1959: Longford. Geol. Atlas 1 mile series, Sheet 47, Geol. Surv., Tas. Dept. Mines.
- Blatt, H., Middleton, G., and Murray, R., 1972: Origin of Sedimentary Rocks. Prentice-Hall Inc., Englewood Cliffs, New Jersey. 634p.
- Brace, W.F., 1961: Dependence of Fracture Strength of Rocks on Grain Size. Proc. 4th Symp. Rock Mech., Univ. Park, Penn.,p.99-103.
- Broch, E., and Franklin, J.A., 1972: The Point Load Strength Test. Int. J. Rock Mech. Min. Sci., v.9, p.669-697 (Pergamon Press, Printed in Great Britain).
- Burley, S.D., 1984: Patterns of diagenesis in the Sherwood Sandstone Group (Triassic), United Kingdom. Clay Minerals, v.19,p.403-440.
- Burrett,C.F., & Martin, E.L., (Eds), 1989: Geology and Mineral Resources of Tasmania. Special Publication 15, Geol. Soc. Aust. Inc.
- Camp, C.L., and Banks, M.R., 1978: A proterosuchian reptile from the early Triassic of Tasmania. Alcheringa, v.2,p.143.
- Carl, J.D., and Amstutz, G.C., 1958: Three-dimensional Liesegang rings by diffusion in a colloidal matrix. Geol. Soc. America Bull., v.69(4), p.1467-1468.
- Carroll, D., 1970: Clay Minerals: A guide to their X-Ray identification. Geol. Soc. America, Special Paper 126.

- Chayes, F., 1949: A simple point counter for thin section analysis. *Am. Mineralogist*, v.34, p.1-11.
- Chilingarian, G.V., & Wolf, K.H., 1975: *Compaction of coarse-grained sediments*. (2 vols), Elsevier, Amsterdam.
- City of Clarence, 1989: *Spirit of Clarence - A Tasmanian Community*. Publ. by City of Clarence.
- Clarke, M.J., & Banks, M.R., 1975: The stratigraphy of the lower (Permo-Carboniferous) parts of the Parmeener Supergroup, Tasmania. *In*: Campbell, K.S.W., (Ed.), *Gondwana Geology. Proceedings of the 3rd Gondwana Symposium*, Canberra, p. 453 - 467.
- Clarke, M.J., & Farmer, N., 1976: Bio-stratigraphic nomenclature for Late Palaeozoic rocks in Tasmania. *Pap. Proc. Roy. Soc. Tasm.*, v.110, p. 91-109
- Clarke, M.J., & Baillie, P.W., 1984: *Maria*. *Geol. Surv. Explan. Rept.*, *Geol. Atlas 1:50,000 series, Sheet 77 (8512N)*, Tas. Dept. Mines.
- Clarke, M.J., 1989: Lower Parmeener Supergroup. *In*: Burrett, C.F., & Martin, E.L., (Eds), 1989: *Geology and Mineral Resources of Tasmania*. Special Publ. 15, *Geol. Soc. Aust. Inc.*
- Coleman, J.M., 1969: Brahmaputra River: Channel processes and sedimentation. *Sedimentary Geology*, 3 (Special issue), p.129-239.
- Collinson, J.W., Kemp, N.R., & Eggert, J.T., 1987: Comparison of the Triassic Gondwana Sequences in the Transantarctic Mountains and Tasmania. *Gondwana Six: Stratigraphy, sedimentology, and palaeontology*. Geophysical Monograph 41, American Geophysical Union.
- Conolly, J.R., 1965: Clay mineralogy of some Upper Devonian sediments from central New South Wales. *R.Soc. NSW, J.Proc.*, v.98, p.111-120.
- Cox, R. & G., 1945: *This was Hobart*. Cottage Press, Hobart, Tas.
- Cripps, P., and Spratt, P., 1979: *To Conserve Port Arthur*. Unpubl. Final Rept. by Crawford de Bavay and Cripps, & Fowler, England and Newton, for Tasmanian National Parks and Wildlife Service.
- Cromer, W.C., 1976: Sources of building stone at Port Arthur. Unpubl. Rept. 1976/69, Tas. Dept. Mines.
- Cromer, W.C., Threader, V.M., Knights, C.J., 1976: *Geology of Port Arthur*. Unpubl. Rept. 1976/36, Tas. Dept. Mines.
- Davis, S.N., 1964: Silica in streams and groundwater. *Am. J. Sci.*, v.262, p.870-891.
- Day, M.J., and Goudie, A.S., 1977: Field Assessment of rock hardness using the Schmidt Test Hammer. *British Geomorphological Research Group Technical Bulletin* 18, p.19-29.

- Deer, W.A., Howie, R.A., and Zussman, J., 1966: An Introduction to the Rock-forming Minerals. Longman Group Ltd., London, 528p. (new impression 1971).
- Dreyer, W., 1972: The Science of Rock Mechanics, Pt. 1: The Strength Properties of Rocks. Trans Tech. Publications, Clausthal, Germany, 500pp., Second printing 1973.
- Dunn, J.R., & Hudec, P.P., 1965: The influence of clays on water and ice in rock pores. Bur. of Physical Research, N.Y.S.D.P.W.
- Eggert, J.T., 1983: Petrology, provenance and diagenesis of quartzose and volcanic lithic Triassic fluvial sandstones, Tasmania, Australia. M.Sc. thesis, Ohio State University.
- Erlich, R., Vogel, T.A., Weinberg, B., Kamilli, D.C., Byerly, G., and Richter, H., 1972: Textural variation in petrogenetic analysis. Bull. Geol. Soc. Am., v.83, p.665-676.
- Falvey, D.A., 1974: The development of continental margins in plate tectonic theory. J. Aust. Petrol. Explor. Assoc., v.14, p.95-106.
- Farmer, N., 1981: Kingborough. Geol. Atlas 1:50,000 Series Sheet 8311N, Geol. Surv., Tas. Dept. Mines.
- Farmer, N., 1985: Kingborough. Geol. Surv. Explan. Rept., Geol. Atlas 1:50,000 series, Sheet 88(8311N), Tas. Dept. Mines.
- Fitzhardinge, C.F.R., 1978: Note on Point Load Strength Test. Australian Geomechanics Journal, 1978, p.53.
- Folk, R.L., 1974: Petrology of Sedimentary Rocks. Hemphill Publishing Co., Austin, Texas, 182p. (University of Texas book).
- Forsyth, S.M., Farmer, N., Gulline, A.B., Banks, M.R., Williams, E., & Clarke, M.J., 1974: Status and subdivision of the Parmeener Supergroup. Pap. Proc. Roy. Soc. Tasm., v.108, p. 107-109.
- Forsyth, S.M., Abtmaier, B.F., Leaman, D.E., 1976: Oatlands. Geol. Atlas 1:50,000 series sheet 68(8313S), Geol. Surv., Tas. Dept. Mines.
- Forsyth, S.M., 1984: Oatlands. Explan. Rept., Geol. Atlas 1:50,000 series sheet 68(8313S), Geol. Surv., Tas. Dept. Mines.
- Forsyth, S.M., 1986: Interlaken. Geol. Atlas 1:50,000 series sheet 8313 N (61), Geol. Surv., Tas. Dept. Mines.
- Forsyth, S.M., 1987: Review of the Upper Parmeener Supergroup. Unpubl. Rept. 1987/01, Tas. Dept. Mines.
- Forsyth, S.M., 1989: Interlaken. Geol. Surv. Explan. Rept., Geol. Atlas 1:50,000 Series, Sheet 61 (8313 N), Tas. Dept. Mines.

- Friedman, M., Stearns, D., Nelson, R., & Aguilera, R., 1986: Fractured reservoir analysis. A.A.P.G. School Class Notes, Great Falls, Montana.
- Gere, A., Perry, J., Spry, A., & West, D., 1989: Stone in Modern Buildings - the state of the art. Seminar Papers, Sydney, 23-24th Oct. 1989.
- Gillot, J.E., 1987: Clay in Engineering Geology. *Developments in Geotechnical Geology* 41, Elsevier, Amsterdam, 468p.
- Golding, H.C., 1959: Variation in physical constitution of quarried sandstones from Gosford and Sydney, N.S.W. *J. Proc. Roy. Soc. NSW*, v.93, p.47-60.
- Gore, V., 1938: Liesegang rings in non-gelatinous media. *Kolloidzeitschrift*, 32,p.203-207.
- Green, D.C., 1961: The Geology of the South Arm - Sandford Area, Tasmania. *Pap. Proc. Roy. Soc. Tasm.*, v.95,p.17-34.
- Green, D.C., and Woolley, R.N., 1981: Clay Fraction mineralogy of Triassic sandstones from Port Arthur (and comparison with other rocks for building restoration). Unpubl. Rept. 1981/26, Dept. of Mines Tasmania.
- Green, D.C., 1982: Supplementary report on sandstones from Linden sandstone quarry, New Norfolk. Unpubl. Rept. 1982/20, Tas. Dept. Mines.
- Griffiths, J.C., 1967: Scientific method in analysis of sediments. McGraw-Hill, New York, 508p.
- Grim, R.E., 1962: Applied Clay Mineralogy. McGraw-Hill Book Co. Inc., New York, 422pp.
- Grim, R.E., 1968: Clay Mineralogy. McGraw-Hill Inc., New York, 596p.
- Gulline, A.B., 1982: Sorell. *Geol. Atlas 1:50,000 Series Sheet 8412S*, Geol. Surv., Tas. Dept. Mines
- Hale, G.E., 1962: Triassic System. *In*: Spry, A.H., & Banks, M.R., (Eds) 1962: The Geology of Tasmania. *Jour. Geol. Soc. Aust.*, v.9, part 2, p.217-231.
- Henslowe, D.I., 1972 (?): St. Georges Church. (Pamphlet).
- Hobart Savings Bank, 1945: The Hobart Savings Bank, A Review of it's Century of Progress 1845 - 1945. Walch & Sons, Hobart, Tasmania, 78p.
- Hower, J., Eslinger, E.V., Hower, M., & Perry, E.A., 1976: Mechanism of burial metamorphism of argillaceous sediments. *Bull. Geol. Soc. Am.*, v.87, p.725-737.
- Huggett, J.M., 1984: Controls on Mineral Authigenesis in Coal Measures Sandstones of the east Midlands, U.K. *Clay Minerals*, v.19,p.343-357.

- Johnson, L.J., Chu, C.H., & Hussey, G.A., 1985: Quantitative clay mineral analysis using simultaneous linear equations. *Clays and Clay Minerals*, v.33, no.2, p.107-117.
- Johnston, R.M., 1888: *The Geology of Tasmania*. Govt. Printer, Hobart, Tasmania.
- Kantorowicz, J., 1984: The nature, origin and distribution of authigenic clay minerals from Middle Jurassic Ravenscar and Brent Group sandstones. *Clay Minerals*, v.19, p.359-375.
- Kendall, M.G., & Moran, P.A.P., 1963: *Geometrical Probability*. London, Charles Griffin, 125p.
- Kerr, P.F., 1977: *Optical Mineralogy*. Fourth Edition, McGraw-Hill, New York, 492p.
- Krauskopf, K.B., 1967: *Introduction to Geochemistry*. McGraw-Hill Inc., New York, 721p.
- Larsen, G., and Chilingar, G.V., (Eds), 1967: *Diagenesis in Sediments*. Elsevier, Amsterdam.
- Larsen, G., and Chilingar, G.V., (Eds), 1979: *Diagenesis in Sediments and Sedimentary Rocks*. Elsevier, Amsterdam, 579p., 2nd impression 1983.
- Leaman, D.E., 1971: *The Geology and Groundwater Resources of the Coal River Basin*. Undergr. Water Supply Paper No.7, Tas. Dept. Mines.
- Leaman, D.E., 1972: Hobart. Geol. Atlas 1:50,000 series sheet 82 (8312S), Geol. Surv., Tas. Dept. Mines.
- Leaman, D.E., 1975: Form, mechanism and control of dolerite intrusion near Hobart, Tasmania. *Jour. Geol. Soc. Aust.*, V.22, p.175-186
- Leaman, D.E., *et al.*, 1975: Brighton. Geol. Atlas 1:50,000 series sheet 75(8312N), Geol. Surv., Tas. Dept. Mines.
- Leaman, D.E., 1976: Hobart. Geol. Surv. Explan. Rept., Geol. Atlas 1:50,000 series sheet 82(8312S), Tas. Dept. Mines.
- Leaman, D.E., 1977: Brighton. Geol. Surv. Explan. Rept., Geol. Atlas 1:50,000 series sheet 75(8312N), Tas. Dept. Mines.
- Leder, F., & Park, W.C., 1986: Porosity reduction in sandstone by quartz overgrowth. *A.A.P.G. Bull.*, v.70, p.1713-1728.
- Legge, P.J., 1967: Joints - a synthesis of some of the geological and experimental data published during the last twenty to thirty years. Unpubl. B.Sc. (Hons) Reading Thesis, Uni. of Tas.
- Lewis, M., 1979: In the steps of Hardy Wilson. Unpubl. notes, Uni. of Melbourne.
- Liesegang, R.E., 1945: Geologische Bänderung durch diffusion und kapillarität. *Chemie der Erde*, XV, p.420-423.

- Longiaru, S., 1987: Visual comparators for estimating the degree of sorting from plane and thin section. *Jour. Sedimentary Petrology*, v.57, no.4, July 1987, p.791-794.
- Longman, M.J., 1964: Launceston. One mile Geol. map series, Sheet 8315 S, Tas. Dept. Mines.
- Longman, M.J., 1966: Launceston. Explan. Rept., One mile Geol. map series K'55-7-39, Geol. Surv., Tas. Dept. Mines.
- Martini, I.P., & Banks, M.R., 1989: Sedimentology of the cold-climate, coal-bearing, Lower Permian "Lower Freshwater Sequence" of Tasmania. *Sedimentary Geology*, v.64, p.25-41.
- McBride, E.F., 1989: Quartz cement in sandstones: a review. *Earth Sci. Rev.*, v.26, p.69-112.
- McElhinny, M.W., and Embleton, B.J.J., 1974: Australian palaeo-magnetism and the Phanerozoic plate tectonics of eastern Gondwanaland. *Tectonophysics*, v.22, p.1-29.
- McKellar, J.B.A., 1957: Geology of the Western Tiers near Great Lake, Tasmania. *Rec. Queen Vict. Mus.*, v.7, p.1-13.
- Mellor, M., and Hawkes, I., 1971: Measurement of tensile strength by diametral compression of discs and annuli. *Eng. Geol.* 5, p.173.
- Middleton, M.F., 1982: The subsidence and thermal history of the Bass Basin, southeastern Australia. *Tectonophysics*, v.87, p.383-397.
- Mines Dept. Victoria, 1949: Victorian Building Stones. Reprinted 1949.
- Morad, S., 1984: Diagenetic matrix in Proterozoic graywackes from Sweden. *Jour. Sed. Pet.*, v.54, no. 4, p.1157-1168.
- Morad, S., & AlDahan, A.A., 1987: A SEM study of diagenetic kaolinization and illitization of detrital feldspars in sandstones. *Clay Minerals*, v.22, p.237-243.
- Morrison, R.G., 1988: The Orford Quarries. Unpubl. History, Dept. Lands, Parks & Wildlife, Hobart, Tasmania.
- Muller, G., 1967: *Methods in Sedimentary Petrology*. (Part 1 of "Sedimentary Petrology" by Engelhardt, W., Fuchtbauer H., and Muller, G.) Hafner Publishing Co., New York, 283p.
- Murray, Alexander, 1834 - 36: List of buildings to which Domain Quarry stone was supplied in August 1835. File CSO 1/748/16122, p.154, Archives Office of Tasmania.
- Neumann, B.S., 1976: Lath-shaped montmorillonites in Surrey. *Clay Minerals*, v.11, p.3.

- Nwajide, C.S., & Hoque, M., 1985: Problems of classification and maturity evaluation of a diagenetically altered fluvial sandstone. *Geologie en Mijnbouw*, v.64, p.69-77.
- Ollier, C., 1969: *Weathering*. Longman, London, 304p. (third impression 1976).
- Pacey, N.R., 1984: Bentonites in the chalk of central eastern England and their relation to the opening of the northeast Atlantic. *Earth & Plan. Sci. Lett.*, v.67, p.48-60.
- Pettijohn, F.J., Potter, P.E., and Siever, R., 1973: *Sand and Sandstone*. Springer-Verlag, New York, 618p.
- Pettijohn, F.J., 1975: *Sedimentary Rocks*. Harper & Row, New York, 628p. (Third Edition).
- Pittman, E.F., 1916: Building Stones of the Commonwealth. *Comm. of Australia Official Year Book for 1901 - 1915*, p.446-454.
- Read, J.R.L., Thornton, P.N., and Regan, W.M., 1980: A rational approach to the Point Load Test. The New Zealand Institution of Engineers Proceedings of Technical Groups. v.6, issue 1(G), part 2 (Third Australia- New Zealand Conference on Geomechanics, Wellington, 1980).
- Rigg, A.J., 1970: Permo-Triassic stratigraphy, sedimentation and palaeontology of South Bruny Island. Unpubl. Hons. thesis, Uni. of Tas.
- Robertson, E.G., 1970: *Early Buildings of Southern Tasmania*. Routledge & Kegan Paul Ltd, London.
- Rose, W.I., Chuan, R.L., Cadle, R.D., & Woods, D.C., 1980: Small particles in volcanic eruption clouds. *Am. Jour. Sci.*, v.280, p.671-696.
- Sengupta, M., 1975: A new method of evaluation for dimension stone from diamond drill core. *CIM Bulletin*, July 1975.
- Scherer, M., 1987: Parameters influencing porosity in sandstones: a model for sandstone porosity prediction. *A.A.P.G. Bull.*, v.71, p.485-491
- Schultz, L.G., 1978: Mixed layer clay in the Pierre Shale and equivalent rocks, northern Great Plains region. *U.S. Geol. Surv. Prof. Pap.*, 1064-A, 28p.
- Sharples, C.E., 1984: Distribution of clay types, halite and gypsum in Early Triassic sandstones drilled near Bothwell. Unpubl. Rept. 1984/27, Tas. Dept. Mines.
- Sharples, C.E., Green, D.C., Spratt, P., and Banks, M., 1984: *Tasmanian Building Sandstones*. Unpubl. Rept., Tas. Dept. Mines, prepared for National Estate, Tasmania. 2 vols.
- Sharples, C., 1985a: Ultrasonic Pulse Velocity measurement for rapid field assessment of building sandstone quality. Unpubl. Rept., Tas. Dept. Mines, Oct. 1985, Prep. for National Estate, Tasmania.

- Sharples, C., 1985b: Report on Sandstones in Franklin Square Buildings. Unpubl. Rept. for England, Newton, Spratt & Murphy Pty Ltd, Oct. 1985, Hobart, Tas.
- Sharples, C.E., 1988: Analysis of sandstone in Sarah Island quarries and penitentiary, with recommendations for replacement stone. Unpubl. Rept. for Dept. Lands, Parks & Wildlife, Jan. 1988.
- Sharples, C.E., 1988a: Report on sandstone types and sources used in Savings Bank of Tasmania building, Murray Street, Hobart, Tasmania. Unpubl. Rept. for Law Society of Tasmania, Oct. 1988.
- Sharples, C.E., 1989a: Report on proposed new quarry site, Cobbs Hill, southern Tasmania. Unpubl. Rept. for Etna Stone Pty. Ltd., Feb. 1989.
- Sharples, C.E., 1989b: Elderslie Building Sandstone Quarry. Unpubl. Rept. for Rizzolo Stone & Concrete Pty. Ltd., March 1989.
- Sharples, C. E., 1989c: Geological investigation of sandstone deposit at English Town, northern Tasmania. Unpubl. Rept. for Mr A. Davey & the Tasmanian Development Authority, Aug. 1989.
- Sharples, C. E., 1990: The building and ornamental stone resources of Tasmania. Rept. for Tasmanian Development Authority & Tasmanian Dept. Resour. Ener., April 1990.
- Siever, R., 1982: Geological problems in the geochemistry of sediments. *In Perspectives in Geology. The Survey.* (Circular 525, 1982, State Geol. Surv. Div., Illinois Dept. of Ener. and Nat. Resour.).
- Siever, R., 1986: Burial Diagenesis of Sandstones. In: Mumpton, F.A. (Ed.), 1986, Studies in Diagenesis, U.S. Geol. Surv. Bull. 1578, p.237-248.
- Simon, D.B., and Richardson, E.V., 1961: Forms of bed roughness in alluvial channels. *Amer. Soc. Civil Eng. Proc.* 87, no. HY3, p.87-105.
- Singh, S.K., 1988: Relationship among Fatigue Strength, Mean Grain Size and Compressive Strength of a rock. *Rock Mechanics and Rock Engineering*, v.21, p.271 - 276.
- Slansky, E., 1977: Clay minerals and the quality of artesian waters in the Great Australian Basin in New South Wales. *Search*, v.8, p.322-324.
- Spratt, P.E., 1982: Corrosion at Port Arthur, A.C.A. Conference No.22, Pre-printed papers, Hobart, 8-12 Nov. 1982.
- Spratt, P.E., 1982b: Report on remedial work to stonework, GPO, Hobart. Unpubl. Rept. no. 3688, England, Newton, Spratt & Murphy Pty. Ltd.
- Sprod, D., 1977: Victorian and Edwardian Hobart from old photographs. John Ferguson, Sydney.
- Spry, A., & Banks, M., 1962: The Geology of Tasmania. *Jour. Geol. Soc. Aust.*, v.9, pt.2.

- Spry, A.H., & Solomon, M., 1964: Columnar buchites at Apsley. Q.J.Geol. Soc. Lond., v.120, p.519-545.
- Spry, A.H., 1976: Compressive strength and texture of some Australian quartzites. AMDEL Bull., v.21, p.9-25.
- Spry, A.H., 1978: The Behaviour of Stone. *In* : Second Report of the Salt Damp Research Committee, *including* The Proceedings of the National Conference on Salt Damp held on 20 - 21st March 1978, p.168-176, Adelaide, South Australia.
- Spry, A.H., & Spencer, W.G., 1979: Materials survey: Old Physics and Quadrangle buildings. AMDEL Unpubl. Rept. No.1255.
- Spry, A.H., 1981: The Conservation of Masonry Materials in historic buildings. AMDEL Unpubl. Rept. No.1381, for Dept. for the Environment, S.Australia.
- Spry, A.H., 1982: Australian Sandstone Supply. AMDEL Unpubl. Progress Rept. No.1, Project 2/21/4, CSIRO.
- Spry, A.H., 1983: Australian Building Sandstones. AMDEL Unpubl. Rept. No.1502, for CSIRO Division of Building Research.
- Spry, A.H., 1988: Building Stone Seminar. (papers presented) Alan H. Spry & Associates, Adelaide, South Australia, 18-21 April 1988.
- Srodon, J., 1981: X-Ray identification of randomly inter-stratified illite-smectite in mixtures with discrete illite. Clay Minerals, v.16, p.297-304.
- Standards Association of Australia, 1983: Draft Australian standard: Methods for sampling and testing aggregates: water absorption, apparent porosity and bulk density of building stone. Draft Standard CE/12/6/4/83-20, Nov. 1983.
- Starkey, H.C., Blackmon, P.D., and Hauff, P.L., 1984: The routine mineralogical analysis of clay-bearing samples. U.S. Geol. Surv. Bull. 1563.
- Stern, K.H., 1954: The Liesegang Phenomenon. Chem. Rev., v.54, p.79-99.
- Sudo, T., Shimoda, S., Yotosumoto, H., & Aita, S., 1981: Electron Micrographs of Clay Minerals. Developments in Sedimentology 31, Elsevier, Amsterdam.
- Summa, L.L., & Verosub, K.L., 1987: A catalog of North American ashes found in altered and unaltered states for use as a data base in studying tephra diagenesis. Jour. Volc. & Geotherm. Res., v.32, p.321-327.
- Tas. Cyclopaedia, 1931: Tasmanian Cyclopaedia.
- Thorez, J., 1975: Phyllosilicates and clay minerals; A laboratory handbook for their X-Ray diffraction analysis. Editions G.Lelotte, B 4820 Dison, Belgium.
- Threader, V.M., 1969: Proposed quarry at Pontville. Tas. Dept. Mines, Tech. Rept. 13, p.21.

- Threader, V.M., 1982: Geological investigation at Linden sandstone quarry, New Norfolk. Unpubl. Rept. 1982/7, Tas. Dept. Mines.
- Threader, V.M., & Bacon, C.A., 1983: The Department of Mines Coal Exploration Programme, Fingal Tier. Unpubl. Rept. 1983/46, Tas. Dept. Mines.
- Tickell, F.G., 1965: The techniques of sedimentary mineralogy. Elsevier, Amsterdam, 220p.
- Turner, N.J., & Calver, C.R., 1987: St. Mary's. Geol. Surv. Explan. Rept., Geol. Atlas 1:50,000 Series, sheet 49 (8514 N), Tas. Dept. Mines.
- Twelvetreets, W.H., (date uncertain, early 1900's): Handwritten list of Hobart buildings and quarries. Part of file MIN-44-17, Archives office of Tasmania, Hobart.
- Visher, G.S., 1972: Physical characteristics of Fluvial Deposits. *In*: Rigby, J.K., and Hamblin, W.K., (Eds), 1972, Recognition of Ancient Sedimentary Environments, S.E.P.M. Special Publ. No. 16.
- Walderhaug, O., 1990: A fluid inclusion study of quartz-cemented sandstones from offshore mid-Norway - possible evidence for continued quartz cementation during oil emplacement. *Jour. Sed. Pet.*, v.60, p.203-210.
- Weaver, C.E., and Pollard, L.D., 1973: The Chemistry of Clay Minerals. Elsevier, Amsterdam, 213p.
- Whiteley, R.J., 1983: Recent developments in the application of geophysics to geotechnical investigation. *In* Ervin, M.C., (Ed) 1983: In-situ testing for geotechnical investigations. A.A. Balkema, Rotterdam, 131p.
- Williams, R.B.G., and Robinson, D.A., 1983: The effect of surface texture on the determination of the surface hardness of rock using the Schmidt hammer. *Earth Surface Processes and Landforms*, v.8, p.289-292.
- Wilson, L., & Huang, T.C., 1979: The influence of shape on the atmospheric settling velocity of volcanic ash particles. *Earth and Plan. Sci. Lett.*, v.44, p.311-324.
- Wilson, M.D., & Pittman, E.D., 1977: Authigenic clays in sandstones: recognition and influence on reservoir properties and palaeo-environmental analysis. *Jour. Sed. Pet.*, v.47, p.3-31.
- Winkler, E.M., 1973: Stone: Properties, durability in man's environment. Springer-Verlag, Wien - New York, 230p.
- Záruba, Q., & Mencl, V., 1976: Engineering Geology. Elsevier, Amsterdam, 504p.

APPENDICES

APPENDIX ONE

SANDSTONE SOURCE DATA SHEETS

This appendix lists the data obtained on Tasmanian building sandstone sources in the course of this project. It is not an exhaustive list of every quarry which has ever been used: many buildings, especially in rural areas, were constructed using small local sources which may have only been used for one or two buildings.

However, the quarries listed here comprise most of the major historical quarries, and all of the quarries which are presently worked, or have been in the recent past.

Sandstone properties and test results listed are described in Chapter Two and Appendix Three. Probably the most important data which were not obtained for all specimens during this work were wet strength, inter-granular texture data (see section 2.3.4), and volume percentage of mineral types in each specimen (obtainable by thin section point counting). Only the volume percentage of clay matrix was obtained in most cases.

In interpreting the data sheets, the following points should be noted:

1) Known usage

Known usage of stone is recorded as either:

- | | |
|------------------|--|
| Dimension stone: | Blocks of brick size or larger. |
| Flagging stone: | Thin slabs of planar-bedded stone, generally used as ornamental paving or feature walls. |

2) Specimen freshness

Sandstone properties (particularly effective porosity and strength) are most reliably measured on fresh sub-surface samples, since surface weathering may significantly alter such properties. However, in some cases it was only possible to obtain more or less weathered specimens from old buildings or natural outcrops.

Specimen freshness is indicated by the following symbols against each specimen number on the data sheets:

- * - Fresh sample from quarry or borehole.
- + - Weathered outcrop sample (natural outcrop or old quarry face).
- # - Weathered sample from building.

3) Physical properties

Point Load Strength Indices were measured on specimens air-dried at 20° C.

The average Point Load Strength Indices and Ultrasonic Pulse Velocities calculated normal and parallel to bedding cannot necessarily be recalculated to yield the quoted average value for all directions, since for practical reasons it was not always possible to take the same number of measurements in each of the two standard directions.

4) Mineralogy

If they were identified in XRD analysis, halite and gypsum are indicated by a simple "P". Since these minerals are liable to be partly washed out or diluted during XRD slide preparation, percentage values would be misleading. Gypsum and halite may precipitate in sandstone during weathering (either in natural outcrops or buildings), as well as during deposition or diagenesis.

5) Observed durability of stone in buildings

For the purposes of these data sheets, the following three classifications are adopted to describe observed durability of sandstones in use in buildings. To attempt a finer classification would be difficult, due to the complexities of stone decay processes.

Good: Little or no decay observed in any part of buildings.

Moderate: Generally little or no decay observed, but some decay noted in high-stress locations.

Poor: Significant decay commonly observed in both high and low stress locations.

Note that this classification does not take into account the period for which a stone has been in use in a building. Thus, a low durability stone may still appear to have good durability in its first few years in a building.

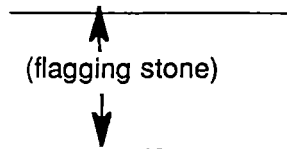
LISTING OF SANDSTONE SOURCES

DOMINANTLY HISTORIC USE (minor modern use only)

- (1) Port Arthur - Plummers Quarry
- (2) Port Arthur - Palmers Lookout Road Quarry
- (3) Port Arthur - Safety Cove Quarry
- (4) Kangaroo Point Green Sandstone Quarry
- (5) Kangaroo Point White Sandstone Quarry
- (6) Gordons Hill Quarries
- (7) Domain Quarries ("Hobart Sandstone")
- (8) Knocklofty Quarry("Stringy Bark Quarries")
- (9) Waterworks Quarries
- (10) Risdon Quarry
- (11) Lindisfarne Quarry
- (12) Ventenat Point Quarry, Bruny Island
- (13) Tea Tree Quarry
- (14) Okehampton Quarry ("Spring Bay Quarry")
- (15) Orford Quarry ("Spring Bay" or "Prossers Bay" Quarry)
- (16) Ross Quarries
- (17) Bothwell - Rifle Range Quarry
- (18) Coningham Quarry
- (19) Ouse Lithic Sandstone Quarry
- (20) Sarah Island Quarries

MODERN USE (some historic use) - SIGNIFICANT

- (21) Pontville Brown Stone Quarry
- (22) Pontville White Stone Quarry (historically "Brighton"?)
- (23) Cobbs Hill Quarry ("Tongatabu Quarry")
- (24) Oatlands Quarry (s)
- (25) Nunamara Quarry (historically "Patersonia Quarry")
- (26) Elderslie Quarry
- (27) Linden Quarry (historically "Bryn Estyn Quarry")
- (28) Buckland Quarry ("The Cobs")
- (29) Molesworth Quarry
- (30) Mike Howes Marsh Quarry
- (31) Kingston Quarry
- (32) Bothwell - Flagging Quarry



MODERN USE (some historic use) - MINOR

- (33) Campania Quarry
- (34) Melton Mowbray Quarry
- (35) Copping Quarry
- (36) Braemar Quarry
- (37) Connorville Quarry
- (38) Lachlan Quarry (flagging stone)

No. 1 SOURCE: Port Arthur - Plummers Quarry (Quarry 1 - stone type 1 - of ref. 1)

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: EN682224 / 43° 8'49"S; 147° 50'22"E
 LOCATION / LAND TENURE: 0.5 km west of Port Arthur township, on property of Mr Plummer.
 KNOWN USAGE: Dimension stone.

DATE(S)	USE
Approx. 1830	Port Arthur penal settlement; together with Palmers Lookout Rd. quarry, this source provided most of the stone used.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Main face up to ten metres high, easily accessible in paddocks.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 001 / PA 1 +;

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic sandstone, possibly very close to base of Triassic. Dolomite contact <200 metres away horizontally.

JOINTING / FRACTURING: Prominent joints in quarry, spacing not recorded.

BEDDING: Horizontal planar bedding, bedding planes 0.05 to >1.0 metres apart.

COLOUR (FRESH, DRY): Pale yellowish-orange (10 YR 8/4) GRAINSIZE: medium SORTING: moderate

COHERENCE: moderate to coherent HOMOGENEITY: homogeneous, uniform

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: minor in outcrop.

OTHER CHARACTERISTICS: minor clay pellets.

PHYSICAL PROPERTIES		SPECIMENS
		PA 1 +
EFFECTIVE POROSITY	(vol.%)	17.25
WATER ABSORPTION	(wt.%)	7.48
DRY BULK ROCK DENSITY	(t/cubic metre)	2.31
DRY POINT LOAD	Av. all directions	0.25
STRENGTH INDEX (MPa)	Av. normal to bedding	0.32
	Av. parallel to bedding	0.18
ULTRASONIC	Av. all directions	1897
PULSE VELOCITY (m/sec)	Av. normal to bedding	1653
	Av. parallel to bedding	2188
MINERALOGY		
QUARTZ	(vol.% of total mineral matter)	?
TOTAL CLAY	(" ")	32
CLAY TYPES	(vol.% of total clay)	
	SMECTITE or ILLITE/SMECTITE mixed layer	67
	ILLITE	33
	KAOLINITE	Trace
	VERMICULITE	-
	CHLORITE	-
	HALITE	-
	GYPSUM	-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST		
VOLUME % LOSS, 10 CYCLES	(V):	100
CYCLE No. FIRST DAMAGE NOTED	(F):	1

OBSERVED DURABILITY OF STONE IN BUILDINGS: Poor; susceptible to salt attack and other severe decay modes (2).

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Very low durability.

REFERENCES: (1) Cromer *et al.* 1976 (2) Cnpps & Spratt 1979 (3) Cromer 1976 (4) Green & Woolley 1981

No. 2 SOURCE: Port Arthur - Palmers Lookout Rd. quarry. (quarry 2 (stone type 2) of refs 1 & 2)

CURRENT STONE LEASE: not current GRID REF. / LATITUDE; LONGITUDE: EN680213 / 43° 9'28" S; 147° 50'13" E
LOCATION / LAND TENURE: Immediately on south side of Palmers Lookout Rd., Port Arthur.
KNOWN USAGE: Dimension Stone.

DATE(S) USE
Approx. 1830 Port Arthur Penal settlement (together with Plummers Quarry stone).

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Large quarry with pick-hewn faces. Adjacent road.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 002 / PA 4 + ; G 400 003 / PA 5 + ;

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic sandstone, possibly close to base of Triassic. No major faulting in area, nearest dolerite contact >0.5 km away horizontally.

JOINTING / FRACTURING: Prominent sub-vertical joints spaced several metres apart.

BEDDING: Cross-bedding ubiquitous, with some over-steepening. Cross-bed lamination 0.01m thick, crossbed sets 0.3 to 1.0 metres thick. Dip 3° towards 166° True.

COLOUR (FRESH, DRY): pale greyish-orange (10 YR 7/2) to yellowish-brown (10 YR 6/4) GRAINSIZE: medium/fine

SORTING: well sorted

COHERENCE: coherent HOMOGENEITY: homogenous

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Black (Mn?) staining common, as thin laminae and irregular blotches. A joint - bounded block within the quarry has suffered major salt-attack decay.

PHYSICAL PROPERTIES		SPECIMENS	
		PA 4 +	PA 5 +
EFFECTIVE POROSITY	(vol.%)	10.11 ?	12.39
WATER ABSORPTION	(wt.%)	4.26 ?	5.16
DRY BULK ROCK DENSITY	(t/cubic metre)	2.38 ?	2.4
DRY POINT LOAD	Av. all directions	1.99 ?	0.31
STRENGTH INDEX (MPa)	Av. normal to bedding	1.29 ?	0.28
	Av. parallel to bedding	2.61 ?	0.35
ULTRASONIC	Av. all directions	3072 ?	2742
PULSE VELOCITY (m/sec)	Av. normal to bedding	2899 ?	2718
	Av. parallel to bedding	3255 ?	2765
MINERALOGY			
QUARTZ	(vol.% of total mineral matter)	-	-
TOTAL CLAY	(" " ")	12 ?	20
CLAY TYPES (vol.% of total clay)			
SMECTITE or ILLITE/SMECTITE mixed layer		100 ?	? (visible under SEM in PA 5)
ILLITE		?	100?
KAOLINITE		?	-
VERMICULITE		-	-
CHLORITE		-	-
HALITE		P	-
GYPSUM		-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST			
VOLUME % LOSS, 10 CYCLES	(V):	4 ?	5
CYCLE No. FIRST DAMAGE NOTED	(F):	7 ?	2

OBSERVED DURABILITY OF STONE IN BUILDINGS: Poor: bad salt attack and other forms of decay common.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Very low durability stone.

REFERENCES: (1) Cromer 1976 (2) Cromer *et al.* 1976 (3) Cripps & Spratt 1979 (4) Green & Woolley 1981

No. 3 SOURCE: Port Arthur - Safety Cove Quarry (This is "Larners Quarry" of ref 1, and Quarry 3 of ref 2)

CURRENT STONE LEASE: not current GRID REF. / LATITUDE; LONGITUDE: EN683186 / 43° 10'55" S; 147° 50'26" E
LOCATION / LAND TENURE: 0.4 km west of old convict farmhouse at Safety Cove, south of Port Arthur.
KNOWN USAGE: Dimension Stone.

DATE(S) USE

Approx. 1830 Port Arthur penal settlement - minor contribution compared with sources 1 & 2.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Several small faces up to three metres high, located on a hillside, hidden and overgrown by scrubby forest.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 004 / PA 2 + ; G 400 005 / PA 3 + ; (from different faces)

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic sandstone, probably close to base of Triassic (ref.3). No known faulting or igneous intrusions nearby (dolerite outcrop approx. 1km east).

JOINTING / FRACTURING: Close fracturing common.

BEDDING: Approx. horizontal, large-scale crossbed sets with laminations 2 - 20mm thick.

COLOUR (FRESH, DRY): Grayish-orange (10 YR 7/4) to pale yellowish-orange (10 YR 8/4) GRAINSIZE: fine & medium (variable)

SORTING: moderate to good COHERENCE: moderate to friable

HOMOGENEITY: Homogeneous except for some colour variation between laminations.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: No iron oxide stain patterning observed.

PHYSICAL PROPERTIES		SPECIMENS	
		PA 2 +	PA 3 +
EFFECTIVE POROSITY	(vol.%)	13.03	14.08
WATER ABSORPTION	(wt.%)	5.67	6.11
DRY BULK ROCK DENSITY	(t/cubic metre)	2.3	2.3
DRY POINT LOAD	Av. all directions	0.22	0.08
STRENGTH INDEX (MPa)	Av. normal to bedding	0.07	0.03
	Av. parallel to bedding	0.4	0.11
ULTRASONIC	Av. all directions	1972	2166
PULSE VELOCITY (m/sec)	Av. normal to bedding	2124	2000
	Av. parallel to bedding	2041	2331
MINERALOGY			
QUARTZ	(vol.% of total mineral matter)	-	-
TOTAL CLAY	(" ")	14	25
CLAY TYPES	(vol.% of total clay)		
	SMECTITE or ILLITE/SMECTITE mixed layer	25	8
	ILLITE	75	92
	KAOLINITE	-	-
	VERMICULITE	-	-
	CHLORITE	-	-
HALITE		-	-
GYPNUM		-	-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST		
VOLUME % LOSS, 10 CYCLES (V):	-	-
CYCLE No. FIRST DAMAGE NOTED (F):	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Uncertain which buildings used this stone; all in poor condition.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Poor durability stone.

REFERENCES: (1) Green & Woolley 1981 (2) Cromer 1976 (3) Cromer *et al.* 1978 (4) Cripps & Spratt 1979

No. 4 SOURCE: Kangaroo Point Green Sandstone Quarry

CURRENT STONE LEASE: not current **GRID REF. / LATITUDE; LONGITUDE:** EN300528 / 42° 52' 34" S; 147° 22' 04" E
LOCATION / LAND TENURE: Bellerive (City of Clarence): Previously thought to have been quarry at site of no. 13 Ormond St. (Ref. 8), but now known to have been on the site currently occupied by the Bellerive Quay building (earlier site of old Council Offices), Savings Bank of Tasmania building and Eastern Shore Indoor Cricket Centre, at corner of Cambridge Rd. & Percy St. (7). Ref. 7 mentions other quarries on King St., Bellerive, but these were in Permian mudstone.

KNOWN USAGE: Dimension stone

DATE(S)	USE
1847	St. Mary's Hospital (cnr. Davey St. & Salamanca Pl., Hobart). Not to be confused with surrounding extensions of Domain stone, or with restoration work (1980's) using Nunamara stone.
~ 1847	Royal Engineers Building, east end Macquarie St., Hobart. (Restoration 1986 using other stones including Nunamara).
1852	St. Marks "Chapel of Ease", cnr. Queen & Scott Streets, Bellerive.
?	Old Law Quadrangle, Melbourne University.

This stone has been grouped together with Kangaroo Pt. White sandstone (source 5) by Spry (ref.5) and others. However the green stone is easily distinguished from the white visually, and must represent a distinct horizon, and most probably a different quarry.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Almost completely built over, except for one remaining face (~ 4m high x 10m long) behind Indoor Cricket Centre. Identification of quarry site supported by pale greenish colour of *in situ* stone being identical to colour of building specimens attributed to this source. Waste cuttings from quarry used as waterfront fill across Cambridge Rd. in area now built over by shops (7).

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 009 / SM 1 # (St. Marks Chapel); MD 1 # (St. Mary's Hospital); M 1 # (Melbourne Uni.); EB 1 # (Royal Engineers Building);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite, Rls of Ref. 1. Faulted contact with Jurassic dolerite occurs within 50m to west of quarry.

JOINTING / FRACTURING: In single existing outcrop, the jointing is subvertical with joint spacings varying from 0.1 to 1.5 metres horizontally.

BEDDING: Many building blocks appear massively bedded. In single existing quarry outcrop, bedding appears massive with a suggestion of very faint cross-bedding.

COLOUR (FRESH, DRY): light greenish-grey (5 GY 8/1) **GRAINSIZE:** varies fine to coarse. Fine in single existing outcrop.

SORTING: moderate/good **COHERENCE:** moderate to friable

HOMOGENEITY: Varies from homogeneous to pebbly and fossiliferous in building blocks. Homogeneous in existing outcrop.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Colour uniform with only minor Liesegang rings seen in a some blocks. Existing outcrop has no Liesegang rings and is predominantly uniformly coloured with only minor pale brown iron oxide staining as bands and irregular patches, mostly within 1.5m of original outcrop surface. Existing outcrop is partly recently excavated and partly an old (quarrying-era?) excavation; old part of excavation shows distinct rounding of edges and fretting of surfaces.

OTHER CHARACTERISTICS: Stone characterised by greenish tinge and high smectite content. Significant variation was present in quarry, from uniform fine-grained stone to medium/coarse stone with quartz pebbles, clay pellets up to 10mm diameter, and vertebrate fossil fragments up to 20mm dia.

PHYSICAL PROPERTIES**SPECIMENS**

		SM 1 #	MD 1 #	M 1 #	EB 1 #
EFFECTIVE POROSITY	(vol.%)	15.48	-	-	-
WATER ABSORPTION	(wt.%)	7.15	-	-	-
DRY BULK ROCK DENSITY	(t/cubic metre)	2.16	-	-	-
DRY POINT LOAD	Av. all directions	0.19	-	-	-
STRENGTH INDEX	Av. normal to bedding	-	-	-	-
(MPa)	Av. parallel to bedding	-	-	-	-
ULTRASONIC	Av. all directions	2178	-	-	-
PULSE VELOCITY	Av. normal to bedding	-	-	-	-
(m/sec)	Av. parallel to bedding	-	-	-	-

MINERALOGY

QUARTZ	(vol.% of total mineral matter)				
TOTAL CLAY	()	45	39	43	-
CLAY TYPES	(vol.% of total clay)				
SMECTITE or ILLITE/SMECTITE mixed layer		56	28	45	87
ILLITE		27	44	18	8
KAOLINITE		17	28	37	5
VERMICULITE		-	-	-	-
CHLORITE		-	-	-	-
HALITE		-	-	-	-
GYP SUM		-	-	P	-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):	-	-	-	-
CYCLE No. FIRST DAMAGE NOTED (F):	-	-	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Very poor; severe exfoliation, deep cracking parallel to block edges, cracking of ledges, pronounced corner rounding. Pick-hewn vertical faces less affected than flat or rendered vertical faces.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Texture variable; durability uniformly very low.

REFERENCES: (1) Leaman 1972, 1976 (2) Lewis 1979 (3) Pittman 1916 (4) Spry 1982 (5) Spry 1983 (6) Sharples *et al* 1984 (7) City of Clarence 1989, p.52

No. 5 SOURCE: Kangaroo Point White Sandstone Quarry (also known as "Bellenve Quarry" (ref. 6))

CURRENT STONE LEASE: Not current **GRID REF. / LATITUDE: LONGITUDE:** EN313535 / 42° 52'13"S ; 147° 22'56" E
LOCATION / LAND TENURE: Probably the old quarry in saddle on west side of Mornington Hill, past end of Quarnes Rd.
KNOWN USAGE: Dimension stone

DATE(S)	USE
1859	Savings Bank of Tasmania, Murray St., Hobart.(1),(6),(7). (Front facade only: basement sides and back appear to be Domain stone - ref. 8).
1861-63	Hobart Museum (2),(3),(6); early white stone parts - columns, dressings, etc ; main walls are of brown Waterworks stone.
1864-66	Hobart Town Hall (2),(3); white stone parts only - brown stone parts are Knocklofty. (Beattie (ref.8) claims white stone is from "Bridgewater Quarry", but he is known to be unreliable.)
?	Freemasons Building, Hobart (2).

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Complex quarry with main face 8 - 10 metres high and many minor faces. Access by 4WD, but quarry still physically workable.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 010 / MHQ 1 + (massive white unit); MHQ 2 + (plane bedded pink stone) ;
 SBT 1 # (Savings Bank of Tas., front facade) ;

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite, Rlq (5) Close to major fault, dolerite outcrops within 200 metres.

JOINTING / FRACTURING: Two major planar joint sets, one dipping 79° towards 77° True, the other dipping 50° towards 29° True. Joint spacing 2 - 3 metres.

BEDDING: Dips 10° towards 197° True. Four metre (+) massive white sandstone bed at quarry base passes up through two metres of white cross-bedded (often over-steepened) stone into the top unit, which is at least six metres of planar (rarely cross-) bedded sandstone, white at base but commonly pink, purple or brown near top.

COLOUR (FRESH, DRY): White (N9) to very pale yellowish-grey (5 Y 9/1) **GRAINSIZE:** medium **SORTING:** moderate/good

COHERENCE: coherent **HOMOGENEITY:** Generally homogeneous, but with minor mudstone beds near top of quarry. Pebbles absent, minor white clay pellets present.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Pink/purple/brown colouration in upper beds due to superficial weathering? Otherwise, iron-oxide staining varies from absent to uniform colouration, to Liesegang rings, blotchy or bedding-controlled staining.

PHYSICAL PROPERTIES		SPECIMENS		
		MHQ 1 +	MHQ 2 +	SBT 1 #
EFFECTIVE POROSITY	(vol.%)	16.05	-	-
WATER ABSORPTION	(wt.%)	6.71	-	-
DRY BULK ROCK DENSITY	(t/cubic metre)	2.39	-	-
DRY POINT LOAD	Av. all directions	0.17	-	-
STRENGTH INDEX (MPa)	Av. normal to bedding	-	-	-
	Av. parallel to bedding	-	-	-
ULTRASONIC	Av. all directions	2355	-	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	-	-
	Av. parallel to bedding	-	-	-
MINERALOGY				
QUARTZ	(vol.% of total mineral matter)	-	-	-
TOTAL CLAY	(" " ")	28	38	-
CLAY TYPES (vol.% of total clay)				
SMECTITE or ILLITE/SMECTITE mixed layer		1	5	-
ILLITE		20	17	7
KAOLINITE		79	78	93
VERMICULITE		-	-	-
CHLORITE		-	-	-
HALITE		-	-	-
GYPSUM		-	-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST				
VOLUME % LOSS, 10 CYCLES	(V):	< 5	-	-
CYCLE No. FIRST DAMAGE NOTED	(F):	6	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: S.B.T. Building - moderate (generally good, a few deep cracks); In quarry, stone in poor condition - sanding and honeycomb weathering at (wet) base of main face.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Performance likely to be good except where exposed to salt and damp (high porosity / low strength make stone susceptible). Somewhat variable in bedding structure and texture (pellets, etc).

REFERENCES: (1) Spry 1982 (2) Twelvetrees, date uncertain (3) Robertson 1970 (4) Spry 1983 (5) Leaman 1972 (6) Beattie, date uncertain (7) Hobart Savings Bank 1945 (8) Sharples 1988a

No. 6

SOURCE: Gordons Hill Quarries

CURRENT STONE LEASE: not current GRID REF. / LATITUDE; LONGITUDE: EN304551 / 42° 51'19"S ; 147° 22'21"E
 LOCATION / LAND TENURE: Private land on saddle east of Gordon's Hill, between Warrane and Lindisfarne.
 KNOWN USAGE: Dimension Stone?

DATE(S) USE
 ? ?

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Two small quarries 150 metres apart, faces up to 4 metres high. Easy access.

SPECIMENS (FIELD No.s): GH 1 + (NW quarry) ; GH 2 + (SE quarry, near base);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Quartz arenite; Early Triassic Riq (1)

JOINTING / FRACTURING: -

BEDDING: NW quarry: planar bedding; SE quarry: Three metre thick massive unit at base, overlain by cross-beds.

COLOUR (FRESH, DRY): pale pink-brown to pale brown and white. GRAINSIZE: - SORTING: -

COHERENCE: - HOMOGENEITY: -

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: - Banding minor or absent

PHYSICAL PROPERTIES		SPECIMENS	
		GH 1 +	GH 2 +
EFFECTIVE POROSITY	(vol.%)	13.39	15.80
WATER ABSORPTION	(wt.%)	-	-
DRY BULK ROCK DENSITY	(t/cubic metre)	-	-
DRY POINT LOAD	Av. all directions	1.70	0.39
STRENGTH INDEX (MPa)	Av. normal to bedding	-	-
	Av. parallel to bedding	-	-
ULTRASONIC	Av. all directions	-	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	-
	Av. parallel to bedding	-	-
MINERALOGY			
QUARTZ	(vol.% of total mineral matter)	-	-
TOTAL CLAY	(" " ")	-	-
CLAY TYPES	(vol.% of total clay)		
	SMECTITE or ILLITE/SMECTITE mixed layer	85	65
	ILLITE	14	14
	KAOLINITE	1	21
	VERMICULITE	-	-
	CHLORITE	-	-
HALITE		-	-
GYPHUM		-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST			
VOLUME % LOSS, 10 CYCLES	(V):	-	-
CYCLE No. FIRST DAMAGE NOTED	(F):	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: -

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Very high smectite content indicates poor durability, as do the high porosities.

REFERENCES: (1) Leaman 1972

No. 7 SOURCE: Domain Quarries (also known as "Hobart Sandstone" (ref. 1))

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: Larger: EN271538 / 42° 52'07" S ; 147° 19'53" E
Smaller: EN270533 / 42° 52'16" S ; 147° 19'50" E

LOCATION / LAND TENURE: Thought to have been two separate quarries involved: larger one adjacent Government House (now flooded), and smaller one on the Queens Domain, not far from Domain House.

KNOWN USAGE: Dimension stone.

DATE(S)	USE
1834-38	Old Police Office, cnr Murray & Davey St.'s, (13) (9: buildings D1 & D2).
1835	"New" Customs House (13).
1835	"New Town Church" (prob. St. Johns Anglican Church, St. Johns Park Hospital) (13).
1836-38	St. Georges Church Nave, Battery Point (1) (4) (5) (6) (11).
1840-42	Old Hobart Treasury Building, Murray St. (4) (9: building C) (11)
1841-44	Holy Trinity Church (main building; "dwarf walls" Knocklofty), N. Hobart (2) (3) (4) (11).
1853-57	Government House (2) (3) (7) (8).
1858-64	Old Supreme Court, cnr Murray & Macquarie St.'s, (9: buildings B, & part of A1).
1859	Saving Bank of Tasmania, Murray St. (basement/sides/back; front is Kang.Pt.White) (12).
?	No. 12 Murray St. (= "Chief Secretaries Dept"? (11))
?	"Lands, Works & Survey Offices" Davey St., between Murray St. & Salamanca Place (11); this includes St.Mary's Hospital, which is Kang.Pt.Green stone, but remainder of building is Domain stone.
?	"Old" Public Works Office (4); this may be the Lands, Works & Survey Offices above?

Larger quarry would have ceased operation in 1857-58, when Govt. House completed; date of small quarry closure unknown.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Large quarry flooded; smaller quarry now in Domain reserve. Not visited.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 030 / TR1 # (Trinity Church); 1 #, 2 # (Police Office); 4 #, 16 # (Treasury); 7 #, 11 #, 12 #, 14 #, 15 # (Supreme Court);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite undiff. (RI of ref. 10). Both quarries very close to dolerite contact - within 100 metres (faulted contact near large quarry, Intrusive contact near smaller quarry).

JOINTING / FRACTURING: Unknown. BEDDING: Appears massive in many blocks, but planar and small-scale cross-bedding visible in others.

COLOUR (FRESH, DRY): pale greyish-orange (10 YR 8/4) to light brown (5 YR 6/4)

GRAINSIZE: variable; med. / fine SORTING: variable; moderate to good.

COHERENCE: variable; coherent / friable HOMOGENEITY: Flat clay pellets 3 x 10mm + vary from common to absent; other features present as noted below.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Iron-oxide banding generally minor or absent; some blocks have distinct Liesegang rings or mottling. Pale sub-horizontal anastomosing "stringers" occur in some blocks (suggestive of annealed early fractures).

OTHER CHARACTERISTICS: Round porous spots 10 - 20 mm diameter are a common & characteristic feature, usually slightly darker than surrounding stone and sometimes weathered out. (Liesegang rings, pale stringers, and porous spots occur together in blocks in 12 Murray St.)

PHYSICAL PROPERTIES		SPECIMENS									
		TR1#	1#	2#	4#	7#	11#	12#	14#	15#	16#
EFFECTIVE POROSITY	(vol.%)	18.38	-	-	-	-	-	-	-	-	-
WATER ABSORPTION	(wt.%)	7.63	-	-	-	-	-	-	-	-	-
DRY BULK ROCK DENSITY	(t/cubic metre)	2.15	-	-	-	-	-	-	-	-	-
DRY POINT LOAD	Av. all directions	0.55	-	-	-	-	-	-	-	-	-
STRENGTH INDEX	Av. normal to bedding	-	-	-	-	-	-	-	-	-	-
(MPa)	Av. parallel to bedding	-	-	-	-	-	-	-	-	-	-
ULTRASONIC	Av. all directions	2497	-	-	-	-	-	-	-	-	-
PULSE VELOCITY	Av. normal to bedding	-	-	-	-	-	-	-	-	-	-
(m/sec)	Av. parallel to bedding	-	-	-	-	-	-	-	-	-	-
MINERALOGY											
QUARTZ	(vol.% of total mineral matter)										
TOTAL CLAY	(" " ")	28	-	-	-	-	-	-	-	-	-
CLAY TYPES	(vol.% of total clay)										
SMECTITE or ILLITE/SMECTITE mixed layer		16	10	20	23	57	22	19	86	21	23
ILLITE		34	90	41	40	23	33	81	14	79	38
KAOLINITE		50	-	39	37	20	45	-	-	-	39
VERMICULITE		-	-	-	-	-	-	-	-	-	-
CHLORITE		-	-	-	-	-	-	-	-	-	-
HALITE		-	-	-	-	-	-	-	-	-	-
GYPSUM		P	-	P	-	-	-	P	-	-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST											
VOLUME % LOSS, 10 CYCLES	(V):	-	-	-	-	-	-	-	-	-	-
CYCLE No. FIRST DAMAGE NOTED	(F):	-	-	-	-	-	-	-	-	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Poor; cracking parallel to mortar joints, spitting along bedding, bad exfoliation on window sills & parapets, decay of basal blocks.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Variable texture, uniformly poor durability due to high smectite content; strength and porosity in fresh condition unknown.

REFERENCES: (1) Baker 1915, (2) Spry 1983, (3) Tas. Cyclopaedia 1931, (4) Twelvetroes - date uncertain, (5) Anon. 1964, (6) Henslowe 1972?, (7) Sprod 1977, (8) Cox 1945, (9) Sharples 1985b, (10) Leaman 1972, 1976, (11) Beattie - date uncertain, (12) Sharples 1988a, (13) Murray 1834-36;

No. 8 **SOURCE:** Knocklofty Quarry (also known as "Stringy Bark Quarries" (ref. 8); may include some of "Hobart Sandstone"? (ref.1))

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: EN247523 / 42° 52'52"S ; 147°18'10"E
LOCATION / LAND TENURE: Knocklofty Hill, West Hobart
KNOWN USAGE: Dimension stone.

DATE(S)	USE
1841 - 44	Holy Trinity Church, North Hobart, "Dwarf walls" only (8)
1864 - 66	Hobart Town Hall: Brown Stone (main walling) parts; white stone is from Kangaroo Point white stone quarry. (2) (3) (6) (7) (8)
?	Old AMP Building (Australian Provincial Offices), Hobart; Base course only; ground floor Okehampton stone and other portions Okehampton, Tea-Tree or Brighton stone (2); Beattie (8) says most of building is Tea-Tree - much of other types removed).
? (Pre - 1900)	Old Post Office, Macquane St., Hobart (8)
?	Old Mines, Govt. Printer & Chief Engineer Depts (8) (= New PWO below?)
?	"New" Public Works Office, Hobart (2)

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Very large quarry, main face up to 50 metres high. Not workable; site of present AUSSAT Earth Station.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G400 033 / K2+ (sandstone from fallen block);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Tnassic (Late Gnesbachian - Smithian) quartz arenite of Knocklofty Formation (4), (5). Adjacent major Knocklofty Fault, and top of quarry is less than 40 metres below dolerite sill.

JOINTING / FRACTURING: Complex jointing and fracturing throughout quarry.

BEDDING: Massive, cross-bedded and plane-bedded units all present; dip 8° towards 224° True, with minor warping present. Spec. K2 is massive or faintly plane - bedded.

COLOUR (FRESH, DRY): Pale greyish-orange (10 YR 8/4), although ref. (4) says stone is grey or very pale green when fresh.

GRAINSIZE: medium SORTING: moderate COHERENCE: moderate HOMOGENEITY: homogeneous

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Minor liesegang rings and other minor iron oxide staining. Pale vein-like stringers 2 - 6 mm thick, usually horizontal and spaced 10mm or more apart (similar to Domain Stone) may be a diagenetic effect.

OTHER CHARACTERISTICS: Stone appearance varies through this large quarry; K2 is not necessarily typical.

PHYSICAL PROPERTIES		SPECIMEN
		K2+
EFFECTIVE POROSITY	(vol.%)	10.27
WATER ABSORPTION	(wt.%)	4.67
DRY BULK ROCK DENSITY	(t/cubic metre)	2.20
DRY POINT LOAD	Av. all directions	0.78
STRENGTH INDEX (MPa)	Av. normal to bedding	-
	Av. parallel to bedding	-
ULTRASONIC	Av. all directions	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	-
	Av. parallel to bedding	-
MINERALOGY		
QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" " ")	20
CLAY TYPES	(vol.% of total clay)	
	SMECTITE or ILLITE/SMECTITE mixed layer	13
	ILLITE	19
	KAOLINITE	68
	VERMICULITE	-
	CHLORITE	-
HALITE		-
GYPSUM		-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST		
VOLUME % LOSS, 10 CYCLES	(V):	11
CYCLE No. FIRST DAMAGE NOTED	(F):	7

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not observed.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Likely to be poor durability due to high smectite content and poor salt test results. Likely to be quite variable due to large size of quarry.

REFERENCES: (1) Baker 1915 (2) Twelvetees - date uncertain (3) Robertson 1970 (4) Camp & Banks 1978 (5) Leaman 1972, 1976 (6) Pittman 1916 (7) Spry 1983 (8) Beattie - date uncertain.

No. 9

SOURCE: Waterworks Quarries.

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: EN233490 / 42° 54'39"S ; 147° 17'05"E
 LOCATION / LAND TENURE: Ridgeway Park Reserve, west end of Waterworks reservoirs, south Hobart.
 KNOWN USAGE: Dimension stone (usage below not necessarily from site sampled)

DATE(S)	USE
1868 - 74	St. Davids Cathedral, Hobart. (Original Nave: brown stone parts (1), (4); other parts "Hobart", Tea-Tree and Brighton stone (4)).
1861 - 63	Hobart Museum, brown stone parts (main walling) (1), (2), (4); white dressings are Kangaroo Point White Sandstone.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Site sampled is one of numerous small quarries on hillslopes, mostly overgrown. Not workable - part of Ridgeway Park reserve. Site sampled is small face 4.0 metres high on southern valley slope.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 029 / WW1+ ;

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite "Ris" (3). Site sampled in middle of 1 - 2 km wide fault block, with dolerite sill approx. 80 metres above site.

JOINTING / FRACTURING: Sub-vertical joints up to 2 metres apart, with other random fractures present.

BEDDING: Massive to faintly laminated with interbedded cross-bed units. Dip 24° towards 189° True. Major dip variations in adjacent areas.

COLOUR (FRESH, DRY): This site: pale yellowish grey (5Y 8/1 to 5Y 9/1). Historical use included brown stone.

GRAINSIZE: fine SORTING: moderate COHERENCE: - HOMOGENEITY: Uniform except for iron-oxide nodules.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Dark red-brown iron-oxide nodules up to 50mm diameter are common.

OTHER CHARACTERISTICS: Mica flakes common; black (manganese dioxide?) grains approx. 1.0mm diameter constitute about 1% of the rock.

PHYSICAL PROPERTIES

SPECIMENS

		WW1+
EFFECTIVE POROSITY	(vol.%)	12.82
WATER ABSORPTION	(wt.%)	6.02
DRY BULK ROCK DENSITY	(t/cubic metre)	2.13
DRY POINT LOAD	Av. all directions	0.91
STRENGTH INDEX	Av. normal to bedding	-
(MPa)	Av. parallel to bedding	-
ULTRASONIC	Av. all directions	2088
PULSE VELOCITY	Av. normal to bedding	1855
(m/sec)	Av. parallel to bedding	2320

MINERALOGY

QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" ")	21
CLAY TYPES	(vol.% of total clay)	
SMECTITE or ILLITE/SMECTITE mixed layer		-
ILLITE		100
KAOLINITE		-
VERMICULITE		-
CHLORITE		-
HALITE		-
GYPNUM		-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):	13
CYCLE No. FIRST DAMAGE NOTED (F):	4

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not assessed.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Probable moderate durability, although weathered nature of sample makes assessment difficult. Colour varies from grey to brown between nearby quarry sites.

REFERENCES: (1) Twelvetreets, date uncertain. (2) Robertson 1970 (3) Leaman 1972, 1976 (4) Beattie, date uncertain.

No. 10 SOURCE: Risdon Quarry

CURRENT STONE LEASE: Not current. GRID REF. / LATITUDE; LONGITUDE: approx. EN2657 / 42° 50'18"S ; 147° 19'12"E
LOCATION / LAND TENURE: On present site of Electrolytic Zinc Co. works at Risdon, Hobart.
KNOWN USAGE: Dimension stone.

DATE(S) USE
1901 General Post Office, Hobart (basal damp-courses) (1),(3),(4).

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Precise location uncertain; now covered by E.Z. factory works.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): -

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenites (Ris) (2).

JOINTING / FRACTURING: ?

BEDDING: ?

COLOUR (FRESH, DRY): ? GRAINSIZE: ? SORTING: ?

COHERENCE: ? HOMOGENEITY: ?

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: ?

OTHER CHARACTERISTICS: ?

PHYSICAL PROPERTIES		SPECIMENS
EFFECTIVE POROSITY	(vol.%)	-
WATER ABSORPTION	(wt.%)	-
DRY BULK ROCK DENSITY	(t/cubic metre)	-
DRY POINT LOAD	Av. all directions	-
STRENGTH INDEX (MPa)	Av. normal to bedding	-
	Av. parallel to bedding	-
ULTRASONIC	Av. all directions	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	-
	Av. parallel to bedding	-
MINERALOGY		
QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" " ")	-
CLAY TYPES	(vol.% of total clay)	
SMECTITE or ILLITE/SMECTITE mixed layer		-
ILLITE		-
KAOLINITE		-
VERMICULITE		-
CHLORITE		-
HALITE		-
GYPSUM		-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST	
VOLUME % LOSS, 10 CYCLES (V):	-
CYCLE No. FIRST DAMAGE NOTED (F):	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: ?

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: ?

REFERENCES: (1) Baker 1915 (2) Leaman 1972, 1976 (3) Twelvetrees, date uncertain (4) Beattie, date uncertain.

No. 11 SOURCE: Lindisfarne Quarry

CURRENT STONE LEASE: Not current. GRID REF. / LATITUDE; LONGITUDE: ? EN295561 / 42° 50'49"S; 147° 21'39"E
LOCATION / LAND TENURE: Lindisfarne, Hobart. Built over by houses at No.s 59 - 63 Malunna St. (1)
KNOWN USAGE: Dimension stone

DATE(S)	USE
1860	Walches Building, Macquane St., Hobart. (lower part) (2)
1875 - 77	Derwent & Tamar Building, No.28 Murray St., Hobart (upper pink stone parts; white stone is Tea-Tree stone). (2),(3),(6)
1887 - 89	Baptist Tabernacle, 282 Elizabeth St., North Hobart (main walls; columns and dressings are Ross stone). (6). Restoration 1981.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Possible site now built over.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): -

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite (Riq) (4). Faulted dolerite contact 400 metres horizontally from possible quarry site.

JOINTING / FRACTURING: ?

BEDDING: Cross-bedded.

COLOUR (FRESH, DRY): Distinctive dark pinkish brown stone. GRAINSIZE: - SORTING: -

COHERENCE: - HOMOGENEITY: Uniform in known building blocks.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: No iron-oxide patterning seen in known building blocks.

OTHER CHARACTERISTICS: Dark pinkish colour appears to be a characteristic distinguishing feature of the stone.

PHYSICAL PROPERTIES

SPECIMENS

EFFECTIVE POROSITY	(vol.%)	-
WATER ABSORPTION	(wt.%)	-
DRY BULK ROCK DENSITY	(t/cubic metre)	-
DRY POINT LOAD	Av. all directions	-
STRENGTH INDEX	Av. normal to bedding	-
(MPa)	Av. parallel to bedding	-
ULTRASONIC	Av. all directions	-
PULSE VELOCITY	Av. normal to bedding	-
(m/sec)	Av. parallel to bedding	-

MINERALOGY

QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" " ")	-
CLAY TYPES	(vol.% of total clay)	-
SMECTITE or ILLITE/SMECTITE mixed layer		-
ILLITE		-
KAOLINITE		-
VERMICULITE		-
CHLORITE		-
HALITE		-
GYP SUM		-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES	(V):	-
CYCLE No. FIRST DAMAGE NOTED	(F):	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Moderate durability; generally in good condition, but minor splitting along bedding laminations and parallel to mortar joints noted in Tabernacle.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Appears moderately durable, but little data available.

REFERENCES: (1) Mr Basil Cox, Lindisfarne resident, *pers.comm.* 1983 (2) Spry 1982, 1983 (3) Twelvetreves, date uncertain
(4) Leaman 1972, 1976 (5) Baker 1915 (6) Beattie, date uncertain.

No. 12 SOURCE: Ventenat Point Quarry

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: EN152002 / 43° 21'03"S; 147° 11'13"E
 LOCATION / LAND TENURE: South Bruny Island, at tip and east side of Ventenat Point. Private land and Crown shoreline reserve.
 KNOWN USAGE: Dimension stone.

DATE(S)	USE
1860 - 64	Operated by Thomas Glaister & Co. (Melbourne), stone shipped direct to Taylors Bay, Melbourne (3). Possible subsequent use of quarry by others.
?	Bank of Victoria, Melbourne (1). Later demolished due to poor condition.
1859 - 67	General Post Office, Melbourne: possible use of Ventenat stone plus Orford stone (source 15), (1)

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Worked faces up to 30m high on tip and east side of point. Access by sea or 4WD track.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 006 / V1+ (shoreline outcrop 1km south of quarry); G 400 007 / V2+ (massive bed in quarry); G 400 008 / V3+ (cross-bed unit in quarry);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite. No detailed local mapping available - regional mapping by Rigg (1970). Faulted contact with Permian mudstones adjacent. Nearest known dolerite approx. 3.0 km east.

JOINTING / FRACTURING: Quarry development was controlled by major joint set (joints dip 63° towards 84° True, approx. 3 metre spacing). Secondary joints dip 88° towards 344° True.

BEDDING: Dip 10° towards 254° True in quarry. Both massive and cross-bed units outcrop in quarry. Massive beds 2 - 4 metres thick. Oversteepening and slumping present in cross-bed units.

COLOUR (FRESH, DRY): Very light grey (N8)

GRAINSIZE: medium

SORTING: moderate

COHERENCE: moderate

HOMOGENEITY: Generally uniform, but rare clay pellets (V1) and some irregular patches av. 10mm wide of coarser, more porous stone (V3) are present.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Liesegang rings very rare. A few sparse irregular bedding - controlled yellowish orange (10 YR 8/6) iron-oxide stain patches occur.

OTHER CHARACTERISTICS: Stone may be affected by proximity of sea-salt.

PHYSICAL PROPERTIES**SPECIMENS**

		V1+ (@)	V2+	V3+
EFFECTIVE POROSITY (vol.%)		10.47	11.70	9.79
WATER ABSORPTION (wt.%)		4.85	5.15	4.38
DRY BULK ROCK DENSITY (t/cubic metre)		2.16	2.27	2.24
DRY POINT LOAD	Av. all directions	1.29	0.47	1.03
STRENGTH INDEX (MPa)	Av. normal to bedding	1.03	-	0.63
	Av. parallel to bedding	1.52	-	1.29
ULTRASONIC	Av. all directions	3296	2645	3008
PULSE VELOCITY (m/sec)	Av. normal to bedding	3159	-	2876
	Av. parallel to bedding	3433	-	3140

MINERALOGY

QUARTZ (vol.% of total mineral matter)	-	-	-
TOTAL CLAY (" ")	13	17	8
CLAY TYPES (vol.% of total clay)			
SMECTITE or ILLITE/SMECTITE mixed layer	-	22	4
ILLITE	18	17	4
KAOLINITE	82	61	92
VERMICULITE	-	-	-
CHLORITE	-	-	-
HALITE	P	P	P
GYP SUM	-	-	-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):	3	8	-
CYCLE No. FIRST DAMAGE NOTED (F):	2	9	-

(@ = Shoreline natural outcrop; test results affected by salt-related case-hardening?)

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not assessed, although bad salt attack noted in quarry faces.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Probably moderate durability only, and susceptible to salt attack.

REFERENCES: (1) Spry 1982, 1983 (2) Rigg 1970 (3) Morrison 1988

No. 13 SOURCE: Tea-Tree Quarry

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: EN267730 / 42° 41'41"S; 147° 19'38"E
 LOCATION / LAND TENURE: Tea-Tree, southern Tasmania; 400 metres south of Tea-Tree Rd. on property of Mr F.W. Heritage.
 KNOWN USAGE: Dimension Stone

DATE(S)	USE
1841	Possible use in St. Marks Church, Pontville? (or may have used Pontville stone?) (5)
1858 - 64	Supreme Court, Franklin Square, Hobart (window frames & basal layer of bottom two storeys only). (6)
1860	Walches Building, Macquarie St., Hobart (upper part; lower part is Lindisfarne). (4)
1864 - 68	Commercial Bank, Hobart.
1867	Bank of New Zealand, 125 Queen St., Auckland, New Zealand (probably Tea-Tree). (1)
(1890	Quarry briefly re-opened for extensions to B.N.Z.)
1868 - 74	St. Davids Cathedral, Hobart (white stone parts of original nave; Waterworks brown stone mainly used, and possibly also Brighton stone). (2) (10)
1875 - 77	Derwent & Tamar Building, 28 Murray St., Hobart (lower part, white windows, door dressings, cornices; pink stone is Lindisfarne). (2) (4) (10)
1889	General Post Office, Launceston. (3)
(1983	Quarry briefly re-opened for restoration of G.P.O.)
?	Old A.M.P. Building (Australian Provincial Offices?), Hobart. Parts of 2nd floor & new wing of 3rd floor; base was Knocklofty and ground floor Okehampton. Beattie says most of building is Tea-Tree stone: most of other stone types were removed. (2) (10)

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: A line of faces up to 6 metres high and about 300 metres in total length. Main face (at east end) is 55 metres long. Still easily accessible and workable (used briefly in 1983).

SPECIMENS (DEPT. OF MINES No. / FIELD No.): BNZ 1#, BNZ 2# (Bank of N.Z.); G 400 011 / TT3* (main face); G 400 012 / TT4+ (natural outcrop, east of main face, 120m from dolerite contact); G 400 013 / TT5+ (upper face); G 400 014 / TT6+ (small face west of main face, 357m from dolerite); G 400 015 / TT7+ (west end of quarry, 485m from dolerite); G 400 016 / TT8* (main face); G 400 017 / LPO3#, G 400 018 / LPO4# (Launceston GPO);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite Riq (9). Intrusive contact (along pre-existing fault) with dolerite 250m SE of main face. Post-dolerite movement has occurred on fault.

JOINTING / FRACTURING: Large sub-vertical joints up to 10 metres apart. Sawm blocks reveal abundant randomly-oriented deep fractures which may result in up to 75% stone wastage.

BEDDING: Dip 13° towards 209° True. Tabular to wedge-shaped cross-bed sets, oversteepened in places. Minor beds of anastomosing ripples present, and a 1.0 metre thick lense of clay-rich sandstone occurs in middle of main face.

COLOUR (FRESH, DRY): Very light grey (N8) or white (N9), to very pale orange (10 YR 8/2).

GRAINSIZE: fine to medium

SORTING: moderate

COHERENCE: coherent

HOMOGENEITY: Clay pellets common; pale grey/green, up to 50mm long x 3-4mm thick, abundance varies from rare to 5-10% of stone. Rare quartz pebbles approx. 5mm diameter. One metre thick lense of clay-rich sandstone in main face.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Very little iron-oxide colouration (except in one metre clay-rich lense in main face, which has abundant iron staining). No Liesegang rings seen. Minor superficial red and brown colouration (surface weathering).

OTHER CHARACTERISTICS: Small amount of mica on some bedding planes.

PHYSICAL PROPERTIES		SPECIMENS									
		BNZ 1#	BNZ 2#	TT3*	TT4+	TT5+	TT6+	TT7+	TT8*	LPO3#	LPO4#
EFFECTIVE POROSITY	(vol.%)	-	-	12.94	8.89	10.36	11.09	10.54	9.89	10.40	8.90
WATER ABSORPTION	(wt.%)	-	-	5.98	4.01	4.73	4.96	4.78	4.70	4.66	3.91
DRY BULK ROCK DENSITY	(t/cubic metre)	-	-	2.16	2.17	2.19	2.23	2.20	2.10	2.24	2.27
DRY POINT LOAD	Av. all directions	-	-	1.08	0.83	1.02	1.12	1.23	0.49	1.56	1.71
STRENGTH INDEX	Av. normal to bedding	-	-	-	-	0.79	1.01	0.75	0.12	1.20	1.34
(MPa)	Av. parallel to bedding	-	-	-	-	1.17	1.22	1.55	0.87	1.97	2.13
ULTRASONIC	Av. all directions	-	-	2625	2675	2974	2837	2738	2950	2876	2838
PULSE VELOCITY	Av. normal to bedding	-	-	2455	2785	-	-	-	-	-	-
(m/sec)	Av. parallel to bedding	-	-	2794	2963	-	-	-	-	-	-
MINERALOGY											
QUARTZ	(vol.% of total mineral matter)	-	-	-	-	-	-	-	-	-	-
TOTAL CLAY	(" " ")	28	-	13	14	13	13	13	12	17	17
CLAY TYPES	(vol.% of total clay)										
SMECTITE or ILLITE/SMECTITE mixed layer		-	3	19	12	4	2	3	9	9	4
ILLITE		78	55	52	44	42	52	71	24	57	46
KAOLINITE		22	42	29	44	54	46	28	67	34	50
VERMICULITE		-	-	-	-	-	-	-	-	-	-
CHLORITE		-	-	-	-	-	-	-	-	-	-
HALITE		-	-	-	-	-	-	-	-	-	-
GYPSUM		-	P	-	-	-	-	-	-	-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST											
VOLUME % LOSS, 10 CYCLES (V):		-	-	-	-	0.0	-	-	-	3.0	-
CYCLE No. FIRST DAMAGE NOTED (F):		-	-	-	-	>10	-	-	-	5	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Moderate durability: bedding plane splitting on ledges (Launceston GPO); crumbling around mortar joints and on/under lintels where water has collected and percolated through (BNZ). Stone generally in good condition otherwise.
 GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: The stone has reasonable strength and porosity, but possesses swelling clay and fractures which result in excessive wastage. It is a good stone for low-stress situations, but tends to decay in high stress locations.

REFERENCES: (1) E.Joyce & Associates Ltd., Auckland, NZ, *pers.comm.* 1984 (2) Twelvetreets, date uncertain (3) P.Spratt, *pers.comm.* 1983 (4) Spry 1982, 1983 (5) Robertson 1970 (6) Sharples 1985b (7) Baker 1915 (8) Pittman 1916 (9) Leaman *et al.* 1975, Leaman 1977 (10) Beattie, date uncertain.

No. 14

SOURCE: Okehampton Quarry (also known as "Spring Bay Quarry")

CURRENT STONE LEASE: Not current

GRID REF. / LATITUDE; LONGITUDE: EN787906 / 42° 31'57"S; 147° 57'27"E

LOCATION / LAND TENURE: "Okehampton" property of Mr I.D. Weeding, east of Trabunna. Both this and the Orford Quarry have been called "The Spring Bay Quarries" (1)

KNOWN USAGE: Dimension Stone

DATE(S)

USE

1879

Quarry opened (5).

1879 - 89

Major use in Melbourne buildings.

?

Old AMP building (= Australian Provincial Offices?), Hobart. (Ground floor and parts of second floor new wing; base course and other parts of Knocklofty, Tea-Tree and Brighton stone (2) (4). Beattie (4) says much of Okehampton stone was removed and replaced by Tea-Tree stone.)

1889

Quarry closed (5).

1979

Briefly re-opened (east working) by Rizzolo Stone & Concrete Pty Ltd.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Two workings 150m apart above sea-cliffs. Main historical working to the west: 30m high face with tunnel working at base. Would be difficult to re-open. East working equivalent to upper part of west working, minor use only (1979).

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 026 / Oak 1+ (east working); G 400 027 / Oak 2+ (west working);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenites, approx. 100 metres topographically below base of Late Triassic lithic sandstones on Morey's Hill (3). West working is 100 metres NE of an intrusive (?) Jurassic dolerite contact.

JOINTING / FRACTURING: Prominent joints spaced less than one metre to several metres apart, vertical to 60° dip, commonly lined with iron oxides.

BEDDING: Dip 5° towards 104° True. Some massive beds present, but planar to wedge-shaped cross-bed sets (with oversteepening and slumping) common.

COLOUR (FRESH, DRY): Very light grey (N8).

GRAINSIZE: fine - medium.

SORTING: moderate to good.

COHERENCE: Oak 1 friable, Oak 2 coherent.

HOMOGENEITY: Generally uniform, but with clayey and clay pellet - rich horizons (and minor quartz pebbles) in upper parts, especially in east working.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Abundant yellow-orange iron oxide staining, as Liesegang rings, irregular blotches, large uniform patches, etc.

PHYSICAL PROPERTIES

SPECIMENS

Oak 1 +

Oak 2 +

(Oak 1 more weathered ?)

EFFECTIVE POROSITY (vol.%)

13.58

13.28

WATER ABSORPTION (wt.%)

6.19

5.70

DRY BULK ROCK DENSITY (t/cubic metre)

2.19

2.33

DRY POINT LOAD

Av. all directions

0.10

1.67

STRENGTH INDEX

Av. normal to bedding

-

1.35

(MPa)

Av. parallel to bedding

-

1.84

ULTRASONIC

Av. all directions

1576

2837

PULSE VELOCITY

Av. normal to bedding

-

2679

(m/sec)

Av. parallel to bedding

-

2994

MINERALOGY

QUARTZ (vol.% of total mineral matter)

-

-

TOTAL CLAY (" " ")

32

28

CLAY TYPES (vol.% of total clay)

SMECTITE or ILLITE/SMECTITE mixed layer

-

-

ILLITE

-

6

KAOLINITE

100

94

VERMICULITE

-

-

CHLORITE

-

-

HALITE

-

P

GYPSUM

-

-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):

100

8

CYCLE No. FIRST DAMAGE NOTED (F):

3

3

OBSERVED DURABILITY OF STONE IN BUILDINGS: ?

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: East (upper) working: stone sampled appears to be very weathered and of low durability. West (lower) working: moderate durability due to absence of smectite and moderate strength, although porosity is a little high.

REFERENCES: (1) Johnston 1888, p.195-196 (2) Twelvetrees, date uncertain (3) Blake 1958 (4) Beattie, date uncertain (5) Morrison 1988.

No. 15 SOURCE: Orford Quarry (also known as "Spring Bay" or "Prossers Bay" Quarry)

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: EN744864 / 42° 34'15"S; 147° 54'21"E

LOCATION / LAND TENURE: Quarry Point, between Shelly and Spring beaches, Orford. The Okehampton Quarry has also been referred to as "The Spring Bay Quarry".

KNOWN USAGE: Dimension Stone. Major quarry: in 1880 this quarry was Tasmania's second most productive quarry after the "Hobart Quarry" (3).

DATE(S)	USE
1864	Quarry opened (3).
1859 - 67	General Post Office, Melbourne (first stage: two storey building with low tower). (2) (3) ; possible use of Ventenat Point stone also?).
1867 - 70	Town Hall, Melbourne (early part: later parts Stawell sandstone plus limestone). (3) (5)
1874 - 84	Law Courts, Lonsdale St., Melbourne (3).
1887	Quarry closed ? (3)
1900 - 02	?Customs House, Hobart (reputed use in part of building (2), although historical references indicate quarry not worked at this time (3)).

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Cutting into sea-cliffs: approx. 60m along cliffs x 40m in from original cliff face x 10m high face. Access was by sea (metal pins remaining from jetty and derricks still visible on shore platform below quarry).

SPECIMENS (FIELD No.): OR 1 + , OR 2 + (from quarried blocks on quarry floor); M2 # (Law Courts, Melbourne); M3 # (Town Hall, Melbourne);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite (Ross Sandstone) (4); site is over 1.0 km from nearest mapped dolomite outcrop (inland).

JOINTING / FRACTURING: Joint spacing varies 1.0 - 6.0 metres apart laterally.

BEDDING: Cross-bedded (laminations often deformed or overturned) in sets 0.5 - 3.0 m thick. Bedding laminations may be faintly visible as grain-size variations.

COLOUR (FRESH, DRY): Very light grey (N8).

GRAINSIZE: fine (mean 0.25mm dia.)

SORTING: moderate

COHERENCE: moderate to coherent HOMOGENEITY: Several bands of clay pellets noted; one 1.5m thick lense of clay - pellet sandstone in centre of quarry floor is a channel fill.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Brown iron oxide mottling common but not dominant. Orange-brown Liesegang rings occur in places, and are bleached out along some bedding laminations.

PHYSICAL PROPERTIES

SPECIMENS

		OR 1 +	OR 2 +	M2 #	M3 #
EFFECTIVE POROSITY	(vol.%)	10.63	-	-	-
WATER ABSORPTION	(wt.%)	5.19	-	-	-
DRY BULK ROCK DENSITY	(t/cubic metre)	2.04	-	-	-
DRY POINT LOAD	Av. all directions	1.66	-	-	-
STRENGTH INDEX	Av. normal to bedding	1.52	-	-	-
(MPa)	Av. parallel to bedding	1.79	-	-	-
ULTRASONIC	Av. all directions	-	-	-	-
PULSE VELOCITY	Av. normal to bedding	-	-	-	-
(m/sec)	Av. parallel to bedding	-	-	-	-

MINERALOGY

QUARTZ	(vol.% of total mineral matter)	76	-	-	-
TOTAL CLAY	(" " ")	20	-	-	-
CLAY TYPES	(vol.% of total clay)				
SMECTITE or ILLITE/SMECTITE mixed layer		-	-	-	-
ILLITE		24	40	19	4
KAOLINITE		76	60	81	96
VERMICULITE		-	-	-	-
CHLORITE		-	-	-	-
HALITE		-	-	-	-
GYP SUM		-	-	-	P

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):	-	-	-	-
CYCLE No. FIRST DAMAGE NOTED (F):	-	-	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS:-

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Absence of smectite swelling clay, low porosity and moderate strength suggest good durability, although salt attack may occur in extreme situations (as has happened in quarry faces exposed to salt sea spray).

REFERENCES: (1) Lewis 1979 (2) Spry 1982, 1983 (3) Morrison 1988 (4) Blake 1958 (5) Mines Dept. Victoria 1949

No. 16 SOURCE: Ross Quarries

CURRENT STONE LEASE: Not current

LOCATION / LAND TENURE: Four quarries (A - D) on private land on low ridge south of Ross Township. Other minor quarries exist in same area.

GRID REF. / LATITUDE; LONGITUDE: Quarry A: EP41354590 / 42° 02'15"S; 147° 29'58"E

Quarry B: EP41454606 / 42° 02'10"S; 147° 30'04"E

Quarry C: EP41604603 / 42° 02'11"S; 147° 30'10"E

Quarry D: EP40454645 / 42° 01'58"S; 147° 29'20"E

KNOWN USAGE: Dimension stone

DATE(S)	USE (Refs (1), (2))
1825	St. Johns Anglican Church, Launceston (Patersonia/Nunamara stone also used) (Restoration 1982 with Quarry A stone.)
1836	Rose Bridge: original stone from Quarry D, minor restoration in approx. 1978 used quarry C stone.)
?	Ross township buildings: all local buildings presumed to use local stone, much of it from quarry B.
1887 - 89	Baptist Tabernacle, Elizabeth St., Hobart (4). (Columns and dressings only; main walls Lindisfarne stone.)

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: All quarries accessible, and would all be workable (except D ?).

Quarry A: Small faces totalling 5 metres high. Quarry B: Large quarry.

Quarry C: Two faces 2 - 3 metres high. Quarry D: Two small faces 2 metres high.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): QUARRY A: G 400 019 / Ross 1* ; G 400 020 / Ross 2* (cross-bed unit); G 400 021 / Ross 3*

(massive unit); QUARRY B: G 400 022 / Ross 6+ ; QUARRY C: G 400 023 / Ross 7+ ;

QUARRY D: G 400 024 / Ross 4+ ; G 400 025 / Ross 5+ ;

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite (Rp, equivalent to "Ross Sandstone") (3). No major faults known. All quarries within 1.0 km of surface dolerite (intrusive contact) - Quarry A closest (300m).

JOINTING / FRACTURING: Joint/fracture spacing generally several metres. Some joint surfaces coated with iron oxide.

BEDDING: Quarry A: Lower 3 metres massive, upper 2 metres wedge-shaped cross-bed sets with some over-steepening. Dip 6° towards 184° T.

Quarry B: Plane laminated sandstone (very large cross-beds?). Dip 11° towards 189° True.

Quarry C: Large scale cross-bedding (possibly planar laminations at base). Dip 11° towards 189° True.

Quarry D: Tabular and wedge-shaped cross-bed sets with 0.5 metre thick massive interbed. Dip 10° towards 189° True.

COLOUR (FRESH, DRY): Very light grey (N8) to light greenish grey (5 YR 8/1) or very pale orange (10 YR 8/2).

GRAINSIZE: fine to medium

SORTING: well sorted

COHERENCE: coherent

HOMOGENEITY: Clay pellets absent from Quarry A, minor in quarries B and D, common in quarry C. Minor mudstone bands near top of quarry A.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Variable iron oxide staining: some stone unstained, other stone (especially in quarry A) has abundant mottles, bands and Liesegang rings of yellow-orange colour.

OTHER CHARACTERISTICS: Mica common on bedding planes in some places.

PHYSICAL PROPERTIES		SPECIMENS						
		Ross 1*	Ross 2*	Ross 3*	Ross 4+	Ross 5+	Ross 6+	Ross 7+
EFFECTIVE POROSITY	(vol.%)	15.86	17.09	15.89	13.71	12.63	13.95	15.92
WATER ABSORPTION	(wt.%)	7.19	8.34	7.33	6.07	6.19	6.12	7.34
DRY BULK ROCK DENSITY	(t/cubic metre)	2.21	2.05	2.17	2.26	2.04	2.28	2.17
DRY POINT LOAD	Av. all directions	0.34	0.91	0.43	1.27	0.28	0.68	0.55
STRENGTH INDEX (MPa)	Av. normal to bedding	0.16	0.88	-	0.63	0.05	0.33	0.29
	Av. parallel to bedding	0.55	0.94	-	2.01	0.39	0.99	0.73
ULTRASONIC	Av. all directions	2527	2865	2448	3454	-	3045	2755
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	2748	-	3333	-	2887	2632
	Av. parallel to bedding	-	2983	-	3575	-	3204	2845
MINERALOGY								
QUARTZ	(vol.% of total mineral matter)	-	-	-	-	-	-	-
TOTAL CLAY	(" " ")	33	27	35	30	30	27	27
CLAY TYPES	(vol.% of total clay)							
	SMECTITE or ILLITE/SMECTITE mixed layer	-	-	-	-	-	-	-
	ILLITE	57	48	78	31	40	65	40
	KAOLINITE	43	54	22	69	60	35	60
	VERMICULITE	-	-	-	-	-	-	-
	CHLORITE	-	-	-	-	-	-	-
	HALITE	-	-	-	P	P	-	-
	GYP SUM	-	-	-	-	-	-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST								
VOLUME % LOSS, 10 CYCLES (V):		23	12	7	-	-	-	-
CYCLE No. FIRST DAMAGE NOTED (F):		4	2	5	-	-	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS. Most Ross buildings in good condition, but with minor salt attack at ground level in some cases.

In St. Johns Church some splitting along ledges and crumbling adjacent to mortar joints has occurred.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Due to complete absence of swelling clay, a reasonable stone for use in salt-free environments. High porosity and low strength would make the stone susceptible to salt attack.

REFERENCES: (1) Pittman 1916 (2) Spry 1982, 1983 (3) Forsyth 1986 (4) Beattie, date uncertain.

No. 17

SOURCE: Bothwell - Rifle Range Quarry

CURRENT STONE LEASE: 1318 P/M (36 ha., pegged 19/11/1987, by Rizzolo Stone & Concrete Pty. Ltd.)

GRID REF. / LATITUDE; LONGITUDE: EP018058 / 42° 24' 00" S; 147° 01' 19" E

LOCATION / LAND TENURE: Approx. 2.0 km SE of Bothwell, on Rifle Range Hill. Private freehold, property of Rothamay Pastoral Co. (Mr Colin Campbell).

KNOWN USAGE: Dimension stone.

DATE(S)	USE
1896	Church of England, Bothwell (Nave; tower added 1921, reputedly of stone from western working of quarry, although this seems doubtful as western stone much lower quality. Most stone in church is from east working?) (1).
?	Old School House, Bothwell (inbetween Church of England and St. Lukes Church). Smooth window columns; rough stone from Barrack Hill. (1).
1989	Rizzolo Stone and Concrete Pty. Ltd. currently negotiating with a view to re-open east working of quarry.

All use of stone to date in local Bothwell buildings.
Other minor quarries exist in Bothwell area: Barrack Hill (just west of township, stone taken from around crest of hill and used locally in St. Lukes Presbyterian Church, Town Hall, and old barracks on Barrack Hill; (1)), and on north side of the low "Nant Hill" approx. 3.0 km north of Barrack Hill. (1)

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Main (eastern) working consists of old faces up to 3.5 metres high and about 40 metres long. Western working consists of shallow pits approx. 200 metres west of main working.

SPECIMENS (FIELD No.): West working: Bo 1 +; East (main) working: Bo 2 +; RR 4 +.

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite (Rp). Approx. 150 metres SE of intrusive dolerite contact (2).

JOINTING / FRACTURING: Prominent sub-vertical joints spaced 1 - 2 metres horizontally strike 299° True. Secondary sub-vertical joints 1 - 3 metres apart strike between 323° and 23° True. Irregular fracturing occurs in a few limited zones.

BEDDING. Main (east) working: Exposed face is a massive bed except for 0.3 m thick cross-bed horizon in middle of face. Base of massive unit not exposed, but poorly exposed plane-bedded unit immediately overlies the main face. Bedding dips 5° towards east.

COLOUR (FRESH, DRY): Creamy white to very pale orange (10 YR 8/4), sometimes with faint pink tinge.

GRAINSIZE: medium SORTING: moderately well sorted COHERENCE: East (main) face: coherent; West working: soft & friable.

HOMOGENEITY: Uniform and homogeneous apart from clay pellets in thin cross-bed horizon, and mica on bedding planes in upper plane-bedded unit.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: East (main) face: Liesegang rings and orange - red iron oxide stain blotches abundant for at least 300mm into stone from joint/outcrop surfaces in most parts of face. "Bleached" white patches 20 - 30mm dia. are commonly super-imposed upon (ie, truncate) the iron oxide stain patterns. Some stone masses in the east face are nearly free of iron oxide staining, although proportions of stained to unstained stone bulk are presently unknown.

PHYSICAL PROPERTIES		SPECIMENS		
		Bo 1+	Bo 2+	RR 4+
EFFECTIVE POROSITY	(vol.%)	11.82	10.12	12.64
WATER ABSORPTION	(wt.%)	5.02	4.62	6.05
DRY BULK ROCK DENSITY	(t/cubic metre)	2.30	2.17	2.09
DRY POINT LOAD	Av. all directions	-	-	2.38
STRENGTH INDEX (MPa)	Av. normal to bedding	-	-	-
	Av. parallel to bedding	-	-	-
ULTRASONIC	Av. all directions	-	-	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	-	-
	Av. parallel to bedding	-	-	-
MINERALOGY				
QUARTZ	(vol.% of total mineral matter)	-	-	-
TOTAL CLAY	(" " ")	-	20	20
CLAY TYPES (vol.% of total clay)				
	SMECTITE or ILLITE/SMECTITE mixed layer	33	-	-
	ILLITE	27	50	26
	KAOLINITE	40	50	74
	VERMICULITE	-	-	-
	CHLORITE	-	-	-
	HALITE	-	-	-
	GYPSUM	-	-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST				
VOLUME % LOSS, 10 CYCLES	(V):	-	-	-
CYCLE No. FIRST DAMAGE NOTED	(F):	-	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: No sign of any physical deterioration whatever in Bothwell Church of England (after 90 years exposure)

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Very high durability of stone in main east face indicated by high strength, good porosity, absence of smectite, and performance in church. Abundance of smectite in west working would suggest poor performance in that stone.

REFERENCES: (1) Mr Albert Goggins, Bothwell (retired stonemason) *pers. comm.* 1985 (2) Forsyth *et al.* 1976

No. 18 SOURCE: Coningham Quarry

CURRENT STONE LEASE: Not Current GRID REF. / LATITUDE; LONGITUDE: -
LOCATION / LAND TENURE: On shoreline between Snug Bay and Coningham Beach, near Hurst Point, Snug, southern Tasmania.
KNOWN USAGE: ?

DATE(S) USE
? ?

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Abandoned, not visited during this work.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): Not sampled

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Tnassic sandstone

JOINTING / FRACTURING: ?

BEDDING: ?

COLOUR (FRESH, DRY): ? GRAINSIZE: SORTING:

COHERENCE: HOMOGENEITY:

DIAGENETIC/WEATHERING COLOURATION/EFFECTS:

OTHER CHARACTERISTICS:

PHYSICAL PROPERTIES		SPECIMENS
EFFECTIVE POROSITY	(vol.%)	
WATER ABSORPTION	(wt.%)	
DRY BULK ROCK DENSITY	(Vcubic metre)	
DRY POINT LOAD	Av. all directions	
STRENGTH INDEX	Av. normal to bedding	
(MPa)	Av. parallel to bedding	
ULTRASONIC	Av. all directions	
PULSE VELOCITY	Av. normal to bedding	
(m/sec)	Av. parallel to bedding	

MINERALOGY
QUARTZ (vol.% of total mineral matter)
TOTAL CLAY (" ")
CLAY TYPES (vol.% of total clay)
SMECTITE or ILLITE/SMECTITE mixed layer
ILLITE
KAOLINITE
VERMICULITE
CHLORITE
HALITE
GYPSUM

SODIUM CHLORIDE SALT CRYSTALLISATION TEST
VOLUME % LOSS, 10 CYCLES (V):
CYCLE No. FIRST DAMAGE NOTED (F):

OBSERVED DURABILITY OF STONE IN BUILDINGS: ?
GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: ?
REFERENCES: -

No. 19

SOURCE: Ouse - Lithic Sandstone Quarry

CURRENT STONE LEASE: Not current

GRID REF. / LATITUDE; LONGITUDE: ?

LOCATION / LAND TENURE: Quarry location uncertain; presumably within areas of Late Triassic lithic sandstone known to exist within Ouse region.

KNOWN USAGE: Dimension stone

DATE(S)
1842 -43USE
St. John the Baptist Anglican Church, Ouse (Entire building originally of lithic sandstone, but failed blocks replaced with quartz arenite during restoration 1983-84).

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: ?

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 034 / OC 1# (from failed block in Anglican Church).

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Late Triassic lithic arenite.

JOINTING / FRACTURING: ?

BEDDING: Blocks in church appear to be massively bedded.

COLOUR (FRESH, DRY): pale olive-yellow (5 Y 7/4)

GRAINSIZE: medium

SORTING: moderate to poor

COHERENCE: moderately coherent

HOMOGENEITY: Blocks appear homogeneous apart from slightly darker circular spots 1-2mm diameter scattered across sawn surfaces.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: No colour patterning apparent.

PHYSICAL PROPERTIES		SPECIMEN	
		OC 1#	
EFFECTIVE POROSITY	(vol.%)	17.68	
WATER ABSORPTION	(wt.%)	8.13	
DRY BULK ROCK DENSITY	(t/cubic metre)	2.17	
DRY POINT LOAD	Av. all directions	1.14	
STRENGTH INDEX (MPa)	Av. normal to bedding	-	
	Av. parallel to bedding	-	
ULTRASONIC	Av. all directions	-	
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	
	Av. parallel to bedding	-	
MINERALOGY			
QUARTZ	(vol.% of total mineral matter)	-	
TOTAL CLAY	(" " ")	23	
CLAY TYPES	(vol.% of total clay)		
	SMECTITE or ILLITE/SMECTITE mixed layer	?	Very poor X-Ray diffractogram (reason unclear). By comparison with other Tasmanian lithic sandstones, smectite highly likely to be present.
	ILLITE	present	
	KAOLINITE	?	
	VERMICULITE	?	
	CHLORITE	present?	
HALITE		-	
GYPSUM		-	
SODIUM CHLORIDE SALT CRYSTALLISATION TEST			
VOLUME % LOSS, 10 CYCLES	(V):	46	
CYCLE No. FIRST DAMAGE NOTED	(F):	3	

OBSERVED DURABILITY OF STONE IN BUILDINGS: Very poor durability: deep cracking and breaking of blocks in church was threatening structural stability of building prior to 1983 restoration.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Stone has low durability, due to very high porosity, poor salt test results, and probable presence of smectite.

REFERENCES: (1) Mr P. Cripps (architect, Crawford, Cripps & Wegman) *Pers. Comm.* 1983

No. 20

SOURCE: Sarah Island Quarries, (Macquarie Harbour, western Tasmania)

CURRENT STONE LEASE: Not applicable GRID REF. / LATITUDE; LONGITUDE: CP720057 / 42° 23' 24" S; 145° 26' 40" E
 LOCATION / LAND TENURE: NW side of Sarah Island, Macquarie Harbour, western Tasmania. Historic site administered by Dept. of Lands, Parks & Wildlife.
 KNOWN USAGE: Dimension stone.

DATE(S)	USE
1821 - ?mid-1820's	Used in buildings forming Sarah Island penal settlement, particularly the "New" penitentiary.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Shoreline outcrops, quarrying indicated by pick-marks and adjacent stockpiles of shaped blocks. Excavations behind a shoreline path on eastern side of island (just NE of modern jetty) may also have been sources of building stone.

SPECIMENS (FIELD No.): Specimens submitted to Dept. Lands, Parks & Wildlife, Jan. 1988: SI 1 - 4 + from quarries on NW side of Sarah Island; SI 5#, SI 6# from New Penitentiary. (Thin sections of SI 3-6 also submitted).

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Cambrian greywackes (turbidites of a flysch sequence), possibly correlating with Dundas Group. Nearest known igneous rocks are ultrabasics and volcanics approx. 2 km west of island.

JOINTING / FRACTURING: Intense jointing and fracturing in many directions, breaks often as little as 0.1 metres apart. Joint breaks are commonly strongly cemented by brown iron-oxide linings, and many blocks used in buildings contain cemented fractures within them, which are generally more resistant to weathering than surrounding stone.

BEDDING: Dips approx. 70° towards 95° True. Planar to slightly undulating beds 0.1 to 1.0 metres thick, commonly with pronounced major bedding planes. Bed types vary from massive (medium - fine grained) to coarse graded (fining up) beds (a turbidite sequence).

COLOUR (FRESH, DRY): Grey to very pale orange (10 YR 8/2), but colour is dominated by iron oxide patterns (see below).

GRAINSIZE: Fine to coarse grained (SI 4 coarse, other specimens fine - medium grained). SORTING: Poor

COHERENCE: moderate to friable HOMOGENEITY: Sparse quartz pebbles up to 10mm diameter, otherwise stone texturally homogeneous within beds, although grainsize varies between beds.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Stone colour dominated by brown and reddish iron oxide stains as patches, bands, mottles and in some cases Liesegang rings. In thin section, iron oxide appears as dense dark brown masses filling intergranular spaces, or lightly staining clay matrix.

OTHER CHARACTERISTICS: Prominent tectonic cleavage is visible on freshly broken surfaces. Microscopic examination shows cleavage to result from an alignment of clay matrix masses, rather than quartz grains.

PHYSICAL PROPERTIES		SPECIMENS					
		SI 1 +	SI 2+	SI 3+	SI 4+	SI 5#	SI 6#
EFFECTIVE POROSITY	(vol.%)	-	-	11.74	17.70	-	-
WATER ABSORPTION	(wt.%)	-	-	5.73	8.64	-	-
DRY BULK ROCK DENSITY	(t/cubic metre)	-	-	2.03	2.04	-	-
DRY POINT LOAD	Av. all directions	-	-	<0.3	<0.3	-	-
STRENGTH INDEX (MPa)	Av. normal to bedding	-	-	-	-	-	-
	Av. parallel to bedding	-	-	-	-	-	-
ULTRASONIC	Av. all directions	-	-	-	-	-	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	-	-	-	-	-
	Av. parallel to bedding	-	-	-	-	-	-
MINERALOGY							
QUARTZ	(vol.% of total mineral matter)	-	-	49.0	42.6	50.8	45.8
DENSE IRON OXIDE	(" ")	-	-	3.1	33.0	24.6	7.6
TOTAL CLAY	(" ")	-	-	47.6	24.0	23.3	46.0
CLAY TYPES (vol.% of total clay)							
SMECTITE or ILLITE/SMECTITE mixed layer							
ILLITE		56	55	58	52	39	47
KAOLINITE		44	45	42	48	61	53
VERMICULITE		-	-	-	-	-	-
CHLORITE		-	-	-	-	-	-
HALITE		?	?	?	?	?	?
GYPSUM		-	-	-	-	-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST							
VOLUME % LOSS, 10 CYCLES (V):		-	-	-	-	-	-
CYCLE No. FIRST DAMAGE NOTED (F):		-	-	-	-	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Exceptionally poor durability: Rounded edges, crumbling surfaces, very large cavities have formed in many blocks. Total failure of some blocks has led to major collapse of walls of "New" penitentiary.
 GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Very poor durability results from high clay content (= low strength and high porosity). It would be madness to consider further use of this stone!

REFERENCES: (1) Sharples 1988

No. 21

SOURCE: Pontville Brown Stone Quarry

CURRENT STONE LEASE: 812 P/M (12 ha, pegged 28/6/1972, held by Etna Stone Pty. Ltd.)

GRID REF. / LATITUDE; LONGITUDE: EN220734 / 42° 41' 28" S ; 147° 16' 5" E

LOCATION / LAND TENURE: 900 metres SE of Pontville, on east bank of Jordan River. Quarry operated by Etna Stone Pty. Ltd.

KNOWN USAGE: Small dimension stone blocks and slabs, largely for domestic use.

DATE(S)	USE
1968 - Present	Extensive domestic use in Hobart area (homes, etc).
1984	Bowen Bridge (Hobart), eastern abutments.
1985 - Present	Quarry largely worked out, and Etna's operations transferred to Cobbs Hill Quarry (Source 23), but minor extraction of Pontville Brown stone continues on demand.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Good access and easily worked. Wide quarry pit with low (approx. 3 metre) faces; stone extracted by sawing *in situ*.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 038 / Etna 1 * (massive bed, no liesegang rings in specimen);

G 400 039 / Etna 2 * (massive bed with liesegang rings);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite (Rle) (2, 3). Basalt and dolerite outcrop within 100 - 200 metres horizontally.

JOINTING / FRACTURING: A normal fault with several metres movement exists behind north-east (main) face. Central part of quarry largely free of fractures, some other parts intensely fractured. Some fractures have thick Fe-oxide linings.

BEDDING: Bedding dips 14° towards 264° True. Massive bed 2 - 3 metres thick comprises main quarry face. Overlain and underlain by cross-bed horizon with some clay bands and clay pellets. Cross-bed sets planar to wedge - shaped.

COLOUR (FRESH, DRY): Varies with iron - oxide content. Bulk colour very light grey (N8) to pale yellowish - orange (10 YR 8/6).

GRAINSIZE: Fine SORTING: Moderate COHERENCE: moderate to coherent.

HOMOGENEITY: Homogeneous, apart from clay pellets near base of upper cross-bed unit.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Abundant patchily distributed brown iron oxide staining, as liesegang rings, spots and other patterns.

OTHER CHARACTERISTICS: Small (10mm dia.) porous spots weather out to leave small dimples on cut surfaces.

PHYSICAL PROPERTIES		SPECIMENS	
		Etna 1 *	Etna 2 *
EFFECTIVE POROSITY	(vol.%)	10.76	13.01
WATER ABSORPTION	(wt.%)	5.05	5.99
DRY BULK ROCK DENSITY	(t/cubic metre)	2.13	2.18
DRY POINT LOAD	Av. all directions	1.18	0.26
STRENGTH INDEX (MPa)	Av. normal to bedding	-	-
	Av. parallel to bedding	-	-
ULTRASONIC	Av. all directions	2704	2137
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	-
	Av. parallel to bedding	-	-
MINERALOGY			
QUARTZ	(vol.% of total mineral matter)	-	-
TOTAL CLAY	(" ")	18.0	22.0
CLAY TYPES	(vol.% of total clay)		
	SMECTITE or ILLITE/SMECTITE mixed layer	4	1
	ILLITE	85	84
	KAOLINITE	11	15
	VERMICULITE	-	-
	CHLORITE	-	-
HALITE		P	-
GYPSUM		-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST			
VOLUME % LOSS, 10 CYCLES	(V):	25	100
CYCLE No. FIRST DAMAGE NOTED	(F):	2	2

OBSERVED DURABILITY OF STONE IN BUILDINGS: Generally appears to perform fairly well in low stress domestic applications, which is the main application of the stone to date.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Poor performance in salt tests indicate susceptibility to rising damp and salt attack. Strength, porosity and clay composition marginal, indicating stone would have moderate durability in low stress applications, but poor performance likely in high stress applications.

REFERENCES: (1) Threader 1969 (2) Leaman *et al.* 1975 (3) Leaman 1977 (4) Spry 1982, 1983

No. 22

SOURCE: Pontville White Stone Quarry (historically "Brighton"?)

CURRENT STONE LEASE: 724 P/M (1 ha, pegged 17/9/1968, held by Etna Stone Pty. Ltd.)

GRID REF. / LATITUDE; LONGITUDE: EN219733 / 42° 41' 28" S; 147° 16' 01" E

LOCATION / LAND TENURE: 200 metres SW of Pontville Brown stone quarry (Source 21). Owned by Etna Stone Pty. Ltd., but currently operated by Rizzolo Stone & Concrete Pty. Ltd.

KNOWN USAGE: Dimension stone.

DATE(S)	USE
1868 -74	St. David's Cathedral, Hobart - part of original nave (5), (6), (7).
?	Australian Provincial Offices (old AMP building) (7). Originally used for parts of 3rd floor; other parts Knocklofty, Okehampton and Teatree stone. Subsequently much Brighton stone removed from building (7) and most of building restored with Teatree stone.
1968 - Present	Used by Etna & Rizzolo, including St. Davids Cathedral restoration work (4).

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Accessible, currently worked. Approx. 150m diameter pit with 3 metre high faces. Historic use indicated by old pick-hewn faces.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 040 / Etna 3*; R1*; R2*; R3*;

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite: Ris (2), (3); Basalt and dolerite outcrop within 100 - 200 metres horizontally to the south and east.

JOINTING / FRACTURING: Sub-vertical joints spaced 1 - 3 metres apart, with a few "random" joints as well.

BEDDING: Dip 13° towards 214° True. Massive bedding, apart from 1 metre thick cross-bedded unit exposed on southeast side of quarry.

COLOUR (FRESH, DRY): Uniform white (N8 to N9). GRAINSIZE: Fine SORTING: moderate

COHERENCE: moderate to friable HOMOGENEITY: A few 0.2 metre thick clay pellet bands present. Minor black grains < 1.0mm dia. common.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Stone is a uniform ("snowy") white, with no iron oxide staining apart from minor yellow-brown iron stains on fracture surfaces. Stone weathers to yellowish - grey (5 Y 7/2).

OTHER CHARACTERISTICS: Isolated rounded porous patches 10 - 20mm diameter are common, and may weather to leave darker dimples on stone surfaces.

PHYSICAL PROPERTIES		SPECIMENS			
		Etna 3*	R1*	R2*	R3*
EFFECTIVE POROSITY	(vol.%)	12.06	13.11	11.89	14.22
WATER ABSORPTION	(wt.%)	5.72	6.09	5.25	6.16
DRY BULK ROCK DENSITY	(t/cubic metre)	2.11	2.15	2.26	2.31
DRY POINT LOAD	Av. all directions	0.80	0.89	1.63	0.62
STRENGTH INDEX (MPa)	Av. normal to bedding	0.54	-	-	-
	Av. parallel to bedding	1.06	-	-	-
ULTRASONIC	Av. all directions	2629	-	-	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	-	-	-
	Av. parallel to bedding	-	-	-	-
MINERALOGY					
QUARTZ	(vol.% of total mineral matter)	-	-	-	-
TOTAL CLAY	(" " ")	15.0	-	-	-
CLAY TYPES (vol.% of total clay)					
SMECTITE or ILLITE/SMECTITE mixed layer		0.5	1	1	2
ILLITE		83	74	73	75
KAOLINITE		16.5	25	26	23
VERMICULITE		-	-	-	-
CHLORITE		-	-	-	-
HALITE		-	-	-	-
GYPSUM		-	-	-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST					
VOLUME % LOSS, 10 CYCLES (V):		14	-	-	-
CYCLE No. FIRST DAMAGE NOTED (F):		2	-	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Recent work in good condition; old stonework not observed.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Only moderate durability likely: Strength, porosity and swelling clay content are only marginally acceptable. Stone likely to be durable in low stress situations, but will not perform as well in locations susceptible to damp and salt attack.

REFERENCES: (1) Threader 1969 (2) Leaman *et al.* 1975 (3) Leaman 1977 (4) Spry 1982, 1983 (5) Twelvetreets, date uncertain (6) Robertson 1970 (7) Beattie, date uncertain.

No. 23

SOURCE: Cobbe Hill Quarry ("Tongatabu Quarry")

CURRENT STONE LEASE: 818 P/M (21 ha., pegged 14/9/1972, held by Etna Stone Pty. Ltd.)

GRID REF. / LATITUDE; LONGITUDE: EN15857033 / 42° 43' 09" S; 147° 11' 37" E

LOCATION / LAND TENURE: East side of Hesse Gully, top end of Tongatabu Rd. (off Boyer Rd., north of Bridgewater). Private freehold land owned by Etna Stone Pty. Ltd.

KNOWN USAGE: Brick-size dimension stone blocks.

DATE(S)	USE
1985	Quarry opened.
1985 - present	Currently worked by Etna Stone Pty. Ltd., almost exclusively brick-size blocks produced for domestic use (fracturing does not allow extraction of large dimension blocks).

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Presently accessible and working. Pit 27 x 22 metres across, with face up to three metres high. Blocks sawn *in situ*.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): Surface outcrop samples from cross-bed unit 10 - 20 metres below quarry pit:

G 400 041 / Cobb 1+ ; C/2/1+ ; C/3/1+ ; Fresh subsurface samples from quarry pit: Cobb 2* (drill core, depth unknown); C/1/1* (depth 3.0 metres); C/1/2* (depth 0.6 metres);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite (Rls), (1), (2). Quarry approx. 80 metres NE of faulted contact with Permian mudstones; nearest dolerite outcrop approx. 1 km away horizontally.

JOINTING / FRACTURING: Primary joint set sub-vertical, striking 350° - 5° True. Several other joint sets present, plus random fractures. Joints and fractures closely spaced - maximum spacing 1.0 metres.

BEDDING: Dip 14° towards approx. 270° True. Bedding massive in existing quarry pit, underlain by faint large - scale cross-bedding in outcrops below pit.

COLOUR (FRESH, DRY): Pale yellowish-orange (10 YR 8/4)

GRAINSIZE: Medium

SORTING: Moderate

COHERENCE: Very coherent (fresh).

HOMOGENEITY: Quartz pebbles and clay pellets occur in a few narrow bands below quarry pit, but are absent from pit outcrops.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: No iron oxide bands or rings, apart from faint superficial outcrop leeseegang rings.

However, dark brown iron oxide nodules 10 - 15mm diameter are a common feature (up to 40 nodules per metre² of stone surface, variable distribution). A few undulating sub-horizontal bands of paler stone seem to be a leaching phenomenon.

PHYSICAL PROPERTIES

SPECIMENS

		Cobb 1+	C/2/1+	C/3/1+	Cobb 2*	C/1/1*	C/1/2*
EFFECTIVE POROSITY	(vol.%)	12.84	-	-	10.02	9.74	10.09
WATER ABSORPTION	(wt.%)	6.08	-	-	4.30	4.59	4.80
DRY BULK ROCK DENSITY	(t/cubic metre)	2.11	-	-	2.33	2.12	2.10
DRY POINT LOAD	Av. all directions	0.64	-	-	3.94	6.23	4.52
STRENGTH INDEX	Av. normal to bedding	0.64	-	-	3.63	6.96	3.85
(MPa)	Av. parallel to bedding	0.68	-	-	4.24	5.51	5.20
ULTRASONIC	Av. all directions	2255	-	-	-	-	-
PULSE VELOCITY	Av. normal to bedding	-	-	-	-	-	-
(m/sec)	Av. parallel to bedding	-	-	-	-	-	-

MINERALOGY

QUARTZ	(vol.% of total mineral matter)	-	65	73	-	88	79
TOTAL CLAY	(" ")	15	23	21	-	10	13
CLAY TYPES	(vol.% of total clay)						
SMECTITE or ILLITE/SMECTITE mixed layer		4	4	4	-	4	2
ILLITE		8	25	18	45	50	39
KAOLINITE		88	67	75	55	44	50
HALLOYSITE		present	4	3	present	2	9
VERMICULITE		-	-	-	-	-	-
CHLORITE		-	-	-	-	-	-
HALITE		-	-	-	-	-	-
GYPSUM		-	-	-	-	-	-

(present in SEM photos)

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):	37	-	-	-	-	-
CYCLE No. FIRST DAMAGE NOTED (F):	5	-	-	-	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not observed.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Despite presence of trace smectite and halloysite (swelling clays), the high fresh strengths and quartz contents, together with the low porosities and total clay contents, suggest a very high durability for this stone. The salt crystallisation results are deceptive, since they were conducted on a weathered outcrop sample.

REFERENCES: (1) Leaman *et al* 1975 (2) Leaman 1977 (3) Spry 1983 (4) Sharples 1989a

No. 24

SOURCE: Oatlands Quarry (s)

CURRENT STONE LEASE: 1090 P/M (4 ha., pegged 29/7/1982, held by estate of R.T. Fish)

GRID REF. / LATITUDE; LONGITUDE: EP297152 / 42° 18' 50" S; 147° 21' 37" E

LOCATION / LAND TENURE: Modern quarry described herein (some historic use); other historic quarries in district have similar stone (used in construction of historic Oatlands buildings). Modern quarry is on SW outskirts of Oatlands, on private freehold property of Mr R.J. Fish (Parattah).

KNOWN USAGE: Dimension stone.

DATE(S)	USE
This list refers to historic use of Oatlands quarries in general, and modern use of described quarry in particular.	
1800's - 1900's	Various Oatlands buildings.
"	St. Davids Cathedral (part of tower, started 1892, finished 1936)
"	Public Offices, Franklin Square (repairs to balustrades at street level - probably 1880's) (1)
"	Customs House, Hobart (part)
Early 1980's	Use of described quarry by Rizzolo Stone & Concrete Pty. Ltd.; includes:
"	Perpetual Trustees Building, Hobart - restoration.
1988 - current	Use of described quarry by Dunn Monumental Masons Pty. Ltd.; includes:
1988	Stock Exchange building, Macquarie St., Hobart.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Currently accessible and working. Shallow quarry with 2 - 3 metre high faces.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 037 / Riz 1* (main quarry unit; Riz 2* (clay pellet unit at floor of quarry).

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Quartz arenite: Undifferentiated Triassic Ru (4) (Probably Early Triassic Quartz Sandstone Sequence). Nearest dolerite outcrop approx 2 km SW.

JOINTING / FRACTURING: Vertical joints strike 344° True, spaced 3 - 7 m apart (with a 1.0m wide intensely jointed zone in one place). Joints generally lined with black manganese oxide.

BEDDING: Quarry face is a "nearly massive" bed, with faint planar bands 10 - 150mm thick; dip horizontal. Bed 100 - 200mm thick near quarry floor is rich in clay pellets.

COLOUR (FRESH, DRY): Uniform greyish-orange (10 YR 7/4) GRAINSIZE: Fine SORTING: moderate

COHERENCE: moderate HOMOGENEITY: Main quarry unit texturally uniform. In the quarry floor, flat clay pellets (olive-brown [5 Y 4/4], 2 - 40mm diameter) comprise 10 - 20% of stone.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Black manganese oxide "speckles" 1 - 2 mm diameter stain up to 5% of stone in some parts of quarry. No Liesegang rings or other colour patterning - stone colour uniform.

PHYSICAL PROPERTIES

SPECIMENS

		Riz 1*	Riz 2*
EFFECTIVE POROSITY	(vol.%)	18.35	-
WATER ABSORPTION	(wt.%)	7.64	-
DRY BULK ROCK DENSITY	(t/cubic metre)	2.17	-
DRY POINT LOAD	Av. all directions	0.90	-
STRENGTH INDEX	Av. normal to bedding	0.33	-
(MPa)	Av. parallel to bedding	1.40	-
ULTRASONIC	Av. all directions	2223	-
PULSE VELOCITY	Av. normal to bedding	-	-
(m/sec)	Av. parallel to bedding	-	-

MINERALOGY

QUARTZ	(vol.% of total mineral matter)	-	-
TOTAL CLAY	(" " ")	24	-
CLAY TYPES	(vol.% of total clay)		
SMECTITE or ILLITE/SMECTITE mixed layer		3	trace?
ILLITE		55	8
KAOLINITE		7	-
VERMICULITE		35	92
CHLORITE		-	-
HALITE		-	-
GYPSUM		-	-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):	6
CYCLE No FIRST DAMAGE NOTED (F):	2

OBSERVED DURABILITY OF STONE IN BUILDINGS: Moderate durability observed: Oatlands historic buildings generally in good condition, except for very common crumbling and cavity formation at ground level indicating susceptibility to salt damp attack. Some similar weathering of the stone is evident in the quarry face.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Minimal smectite content likely to give stone adequate durability in protected situations. However, low strength and rather high porosity mean that the stone is susceptible to rising damp and salt attack.

REFERENCES: (1) Sharples 1985b (2) Spry 1982, 1983 (3) Robertson 1970 (4) Forsyth *et al.* 1976 (5) Green & Woolley 1981

No. 25

SOURCE: Nunamara Quarry (historically: "Patersonia")

CURRENT STONE LEASE: 1113 P/M (20 ha., pegged 24/4/1983, held by J.Dunn)

GRID REF. / LATITUDE; LONGITUDE: EQ278203 / 41° 22' 07"S; 147° 19' 56"E

LOCATION / LAND TENURE: 300 metres south of A3 highway (turnoff 4.1 km east of St. Patricks River Bridge, Nunamara, NE Tas.). Private land owned by J. Dunn.

KNOWN USAGE: Dimension stone.

DATE(S)	USE
	Historic use ("Patersonia stone"):
1825	St. John's Anglican Church, 157 St. John St., Launceston (massive white sandstone parts).
1860's	Lieutenant Gunn's Monument, Launceston.
	Recent use by Dunn Monumental Masons Pty. Ltd.:
1970's - 1980's	Parliament House, Hobart: northern end extensions
1982 - 1983	Old Mines Department (old "St. Mary's Hospital"): restoration work, including replacement of portal, parapet, window frames, corners.
1986	Royal Engineers Building, Hobart: restoration work, including replacement of entrance pillars.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Accessible by dirt road, currently worked. Main face 7 - 10 metres high x 40 metres long, on moderate slope. An old face immediately west of (and stratigraphically equivalent to) main face is probably historic "Patersonia" quarry.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 044 / N 1* (massive unit, main face); Nav* (average of results on 17 fresh main face samples tested for P.Spratt - private reports 5/11/1984 & 20/5/1985)

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Permian fluvial sandstone beds within Liffey Group (Lower Freshwater Sequence) (3), (4). Sandstone beds are described under "bedding" below, and are overlain by laminated grey mudstone (coastal swale or marsh deposit?) and then by uniform massive sandstone beds with a basal pebble layer and rare ?dropstones. Latter (top) beds appear to represent onset of marine conditions, and possibly represent basal horizon of Upper Marine Sequence. Intrusive dolerite sill occurs approx. 10 - 20 metres above quarry.

JOINTING / FRACTURING: A normal fault, downthrown 6m to the east with fault plane dipping 80°, at east end of the face has caused warping and fracturing in the eastern 15 metres of the main face. Elsewhere in quarry, two main sub-vertical joint systems (major joint set strikes 234° True), with joints spaced 1.0 - 4.0 metres apart, control quarrying operations.

BEDDING: Bedding dips 4° towards 220° True. Main face (quarry product) comprises 2m of faintly cross-bedded sandstone overlain by a thin quartz pebble conglomerate which fines up into a 3.5m massive sandstone bed, overlain by 1.5m of faintly cross-bedded sandstone, then 1.0m of laminated and cross-laminated v. fine sandstone and mudstone, then 3.0m of faintly cross-bedded sandstone with thin interlayers of laminated v. fine sandstone and mudstone. This is overlain by a thick mudstone bed (see above & Fig. 3.2).

COLOUR (FRESH, DRY): Very light grey (N8) to yellow-grey to dusky yellow, (approx. 5 Y 6/3) GRAINSIZE: Fine - medium SORTING: Moderate

COHERENCE: Coherent HOMOGENEITY: Sandstone beds texturally uniform and homogeneous, apart from interbeds noted above. Physical properties measured over 18 samples indicate close uniformity of stone quality throughout quarry.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Orange-brown Liesegang rings and other iron - oxide patterning common, but mainly within 1.0 - 1.5 metres of joints. Stone weathers to dark yellowish-orange (10 YR 6/6) or pale yellowish-brown (10 YR 6/2).

PHYSICAL PROPERTIES		SPECIMENS	
		N 1*	Nav*
EFFECTIVE POROSITY	(vol.%)	10.66	11.99
WATER ABSORPTION	(wt.%)	4.46	-
DRY BULK ROCK DENSITY	(t/cubic metre)	2.39	-
DRY POINT LOAD	Av. all directions	1.19	1.82
STRENGTH INDEX (MPa)	Av. normal to bedding	0.95	-
	Av. parallel to bedding	1.40	-
ULTRASONIC	Av. all directions	2338	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	2143	-
	Av. parallel to bedding	2534	-
MINERALOGY			
QUARTZ	(vol.% of total mineral matter)	-	-
TOTAL CLAY	(" " ")	25	-
CLAY TYPES	(vol.% of total clay)		
	SMECTITE or ILLITE/SMECTITE mixed layer	-	-
	ILLITE	24	sub-dominant
	KAOLINITE	61	dominant
	VERMICULITE	15	minor
	CHLORITE	?	? (suggested by XRD heating and SEM)
HALITE		-	-
GYPSUM		-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST			
VOLUME % LOSS, 10 CYCLES	(V):	3	-
CYCLE No. FIRST DAMAGE NOTED	(F):	10	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Good durability observed in buildings; only decay observed is minor crumbling around mortar joints in St. John's church, probably due to gypsum precipitation.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Good durability for most applications; stone quality uniform through quarry.

REFERENCES: (1) Baker 1915 (2) Pittman 1916 (3) Longman 1964 (4) Longman 1966 (5) Spry 1982, 1983

No. 26

SOURCE: Elderslie Quarry

CURRENT STONE LEASE: 1357 P/M (5 ha., pegged 12/9/1988, held by Rizzolo Stone & Concrete Pty. Ltd.)

GRID REF. / LATITUDE; LONGITUDE: EN08808270 / 42° 38' 28" S; 147° 08' 29" E

LOCATION / LAND TENURE: Quarry located 2.5 km east of Elderslie (35 km north of Hobart), on private Freehold land owned by Sydney Cottage Pty. Ltd.

KNOWN USAGE: Dimension Stone.

DATE(S)	USE
1989	Quarry opened.
July 1989	First use of this stone : Old Supreme Court restoration (Corner Murray and Macquarie Streets, Hobart) : reconstruction of portico cornice/top ("massive" stone used, plus several blocks of cross-bedded stone, lain edge-bedded).

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Access via Elderslie and Cockatoo Gully Roads, then via 2WD track to quarry. Currently worked on several benches to get access to the "massive" stone which is at base of the faces. The topography of the site is such that up to five metres or more of cross-bedded sandstone must be removed to get access to the "massive" bed.

SPECIMENS (FIELD No.): 51/2/1+ (cross-bed unit); 51/2/6*, 51/2/7* ("massive" unit); E1 - 11 (Crossbed unit);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite (Rls). Jurassic dolomite outcrops 250 metres SE of quarry, but a large intervening fault exists 120 metres SE of quarry.

JOINTING / FRACTURING: Sub-vertical joints spaced 5 to 15 metres or more apart. Irregular and polygonal ("pachydermal") fractures occur on weathered surfaces of massive bed (only), but extend only a few centimetres into the outcrop surfaces. These fractures are lined with black manganese oxide films.

BEDDING: Dip 10° towards 214° True. Micaceous plane-laminated bed 0.4 m thick at base of quarry is overlain by a 2.0 to 3.0 metre thick (variable) bed of "massive" sandstone (very faint planar banding visible on fresh surfaces, but no planar splitting tendency evident). "Massive" bed is the "premium quality" building stone, and is overlain by a 10 metre thick unit of cross-bedded stone (laminations distinct, with tendency to split, and convoluted in places), which in turn is overlain by mudstone.

COLOUR (FRESH, DRY): "Massive" stone: yellowish - brown (10 YR 6/4); Cross-bed stone: slightly lighter - yellowish-orange (10 YR 7/6).

GRAINSIZE: Fine SORTING: Moderately well sorted

COHERENCE: coherent HOMOGENEITY: "Massive" stone: Generally homogeneous and uniform; one discontinuous clay lense approx. 20 cm thick and approx. one metre long discovered during initial excavations. Cross-bed stone: Sparse white clay pellets present, more common in bands towards the top of the unit. Cross-bed laminations distinct, lined with abundant mica and black mineral (probably graphite).

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: No Liesegang rings or other iron oxide patterning. The most significant colour patterning is very subtle greenish-brown reduction patches, oval in shape, elongated along bed direction, up to 50 x 150mm in size, occurring in up to 10% of the stone volume ("massive" bed only). Small 3 - 10mm diameter black manganese oxide spots also occur scattered through the stone, but are most abundant close to original weathered surfaces, near joints, and around the edge of greenish reduction spots.

PHYSICAL PROPERTIES		SPECIMENS			
		51/2/1+	51/2/6*	51/2/7*	E1+-11*
EFFECTIVE POROSITY	(vol.%)	11.01	11.65	11.71	(see Section 7.11.1)
WATER ABSORPTION	(wt.%)	5.08	4.97	5.40	
DRY BULK ROCK DENSITY	(t/cubic metre)	2.16	2.34	2.16	
DRY POINT LOAD	Av. all directions	1.15	2.01	-	
STRENGTH INDEX (MPa)	Av. normal to bedding	1.05	-	-	
	Av. parallel to bedding	1.24	-	-	
ULTRASONIC	Av. all directions	-	-	-	
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	-	-	
	Av. parallel to bedding	-	-	-	
MINERALOGY					
QUARTZ	(vol.% of total mineral matter)	81	-	70	
TOTAL CLAY	(" " ")	11	-	22	
CLAY TYPES	(vol.% of total clay)				
	SMECTITE or ILLITE/SMECTITE mixed layer	-	-	-	(trace amounts in some other tested specimens)
	ILLITE	38	34	-	
	KAOLINITE	-	10	-	
	VERMICULITE	62	56	-	
	CHLORITE	-	-	-	
	HALITE	-	-	-	
	GYPSUM	-	-	-	
SODIUM CHLORIDE SALT CRYSTALLISATION TEST					
VOLUME % LOSS, 10 CYCLES	(V):	-	-	-	
CYCLE No. FIRST DAMAGE NOTED	(F):	-	-	-	

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not observed - recent use only.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: The "massive" stone has no or only trace smectite, and has moderate strength and acceptable porosity; it should perform well in protected situations. However, the stone has a high proportion of intergranular clay which results in a low wet/dry strength ratio (2) and significant dimensional instability. The stone may therefore be prone to decay in high stress situations. The cross-bed stone is of similar or slightly better quality in terms of these latter criteria, but has distinct and easily-splitting laminations which limit the applications in which it should be used.

REFERENCES: (1) Leaman *et al.* 1975 (2) Sharples 1989b

No. 27

SOURCE: Linden Quarry (historically "Bryn Estyn")

CURRENT STONE LEASE: 861 P/M (339 ha., pegged 24/9/1973, held by A.T. Ashbolt)
 GRID REF. / LATITUDE; LONGITUDE: DN99956500 / 42° 46' 03" S; 146° 59' 57" E
 LOCATION / LAND TENURE: Off Glenora Rd., 5 km west of New Norfolk, on property of Mr A. Ashbolt.
 KNOWN USAGE: Dimension stone.

DATE(S)	USE
?	Historic use includes:
?	"Bryn Estyn" homestead, near quarry.
?	Old National Mutual Building, Hobart (1)
1901	General Post Office, Hobart - entire building except base courses of Risdon stone. (1) (2) (8)
1973 - 1985	Modern use by Rizzolo Stone & Concrete Pty. Ltd., including:
1975 - 1980	Supreme Court, Salamanca Place, Hobart.
1983	Commonwealth Law Courts, Davey St., Hobart.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Accessible and workable, but not currently operating. Modern (upper) quarry face 45 m long and 4 metres high. Old quarry immediately adjacent to the east.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 035 / L 1+ (massive unit, old quarry); G 400 036 / L 2* (massive unit, new quarry); L 3* (clay pellet only, new quarry);

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite, Ris (3). Nearest dolerite outcrops 500 m to the west (post-dolerite fault forms contact).

JOINTING / FRACTURING: Major joint sets strike N-S (8°T) and E-W (273°T) with up to 2 - 3 metre horizontal joint spacings. Intensely fractured zones are common in the new quarry. Black manganese oxide and brown ferruginous films occur on some joint planes. White bleaching is commonly associated with joint planes.

BEDDING: Dip 8° towards 316° True. Quarried unit is a 6 - 8 metre thick massive bed (minor very subtle bedding structures), underlain by 2 metres of laminated sandstone which in turn is underlain by coarse sandstone. Massive bed is overlain by cross-bed laminated sandstone at top/SW of quarry.

COLOUR (FRESH, DRY): Greyish-orange (10 YR 7/4) GRAINSIZE: Fine - medium SORTING: moderate

COHERENCE: Coherent HOMOGENEITY: Minor clay pellets in lower 2 - 4 metres of massive unit. No pebbles. Quarried unit generally quite uniform and homogeneous.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Moderate brown iron oxide Liesegang rings and figuring concentric about joints: common but subdued colour intensity (stone colour essentially uniform). Very little colour change with weathering - Linden stone in Hobart GPO still greyish - orange 10 YR 7/5.

PHYSICAL PROPERTIES		SPECIMENS			
		L 1+	L 2*	L 3*	ref. 4*
EFFECTIVE POROSITY	(vol.%)	9.11	11.83	-	-
WATER ABSORPTION	(wt.%)	3.91	5.17	-	4.80
DRY BULK ROCK DENSITY	(t/cubic metre)	2.33	2.29	-	2.16
DRY POINT LOAD	Av. all directions	1.82	1.11	-	-
STRENGTH INDEX (MPa)	Av. normal to bedding	-	-	-	-
	Av. parallel to bedding	-	-	-	-
ULTRASONIC	Av. all directions	3020	2575	-	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	-	-	-
	Av. parallel to bedding	-	-	-	-
MINERALOGY					
QUARTZ	(vol.% of total mineral matter)	-	-	-	-
TOTAL CLAY	(" " ")	14	13	100	10
CLAY TYPES (vol.% of total clay)					
	SMECTITE or ILLITE/SMECTITE mixed layer	13	9	1	-
	ILLITE	39	55	84	-
	KAOLINITE	45	36	15	-
	VERMICULITE	-	-	-	-
	CHLORITE	3	?	?	-
	HALITE	-	-	-	-
	GYPNUM	-	-	-	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST					
VOLUME % LOSS, 10 CYCLES (V):		3	<5	-	-
CYCLE No. FIRST DAMAGE NOTED (F):		5	3	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Moderate durability: stone in GPO is generally in excellent condition. However, horizontal splitting has occurred below ledges, due to water-pooling causing smectite-related decay. Minor crumbling evident at base of GPO and Supreme Court, due to rising (salt?) damp.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Durable stone in low stress situations, but smectite content results in decay in situations prone to damp.

REFERENCES: (1) Twelvetees, date uncertain (2) Baker 1915 (3) Leaman 1972, 1976 (4) Threader 1982 (5) Green 1982 (6) Spratt 1982b (7) Spry 1982, 1983 (8) Beattie, date uncertain.

No. 28 SOURCE: Buckland Quarry ("The Cobs")

CURRENT STONE LEASE: 1339 P/M (12 ha., pegged 24/3/1988, held by T.R. Howells, Charles St., Orford, Tas., 7190).

GRID REF. / LATITUDE; LONGITUDE: EN575880 / 42° 33' 29" S; 147° 42' 04" E

LOCATION / LAND TENURE: Six kilometres north of Buckland (via Sand River Rd.), on north side of "The Cobs" hill. Private freehold land belonging to Mr Ted Howells, P.O. Box 298, Orford, Tas., 7190.

KNOWN USAGE: Dimension stone (Trade name: "Cobbs Stone"; not to be confused with Cobbs Hill Quarry Source 23)

DATE(S)	USE
January 1989	Production commenced - mainly domestic applications.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Steep vehicular access. Vertical face 4 - 6 metres high x 50 metres SW to NE, flat ground above face, thus easily workable.

SPECIMENS (FIELD No.): S/Ts/67/1/1*, S/Ts/67/1/3* (Iron-oxide banded); S/Ts/67/1/2*, S/Ts/67/1/4* (pale uniform colouration).

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic Quartz Sandstone Sequence ("Rose Sandstone" (1)); no major mapped faults nearby; intrusive dolerite contact about 200 metres to southwest.

JOINTING / FRACTURING: Joints spaced 10 - 30 metres or more apart; superficial irregular or large-scale pachydermal cracking on weathered outcrop surfaces is common.

BEDDING: Dip 10° towards 95° True. Cross-bedded, sets 0.5 to 2.0 metres thick (very minor massive and plane laminated beds present). Cross-bed laminations very hard to discern on fresh surfaces - minimal spitting tendency, mica rare on laminations.

COLOUR (FRESH, DRY): Very pale grey-white to very pale orange (10 YR 8/2) GRAINSIZE: Fine SORTING: Well sorted

COHERENCE: Moderate HOMOGENEITY: Nearly all exposed stone is texturally uniform (rare clay pellet bands).

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Some parts of quarry are uniformly coloured, free of patterning, while other parts have abundant yellowish-brown (10 YR 5/4) lilesegang nngs, commonly parallel to outcrop surface. All outcrops have randomly distributed circular patches 10 - 200mm diameter of subtly darker colouration than surrounding stone bulk colour. Patches commonly stronger than surrounding stone.

PHYSICAL PROPERTIES

SPECIMENS

		S/Ts/67/1/1*	S/Ts/67/1/3*	S/Ts/67/1/2*	S/Ts/67/1/4*
EFFECTIVE POROSITY	(vol.%)	13.63	12.87	8.97	9.63
WATER ABSORPTION	(wt.%)	6.84	6.30	4.60	4.92
DRY BULK ROCK DENSITY	(t/cubic metre)	1.99	2.04	1.95	1.96

DRY POINT LOAD	Av. all directions	1.25	0.83	1.13	1.37
STRENGTH INDEX	Av. normal to bedding	-	-	-	-
(MPa)	Av. parallel to bedding	-	-	-	-

ULTRASONIC	Av. all directions	-	-	-	-
PULSE VELOCITY	Av. normal to bedding	-	-	-	-
(m/sec)	Av. parallel to bedding	-	-	-	-

MINERALOGY

QUARTZ	(vol.% of total mineral matter)	65	60	78	81
TOTAL CLAY	(" " ")	32	35	18	17
CLAY TYPES (vol.% of total clay)					
SMECTITE or ILLITE/SMECTITE mixed layer		-	-	-	-
ILLITE		30	42	47	44
KAOLINITE		70	58	53	56
VERMICULITE		-	-	-	-
CHLORITE		-	-	-	-
HALITE		-	-	-	-
GYPSUM		-	-	-	-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):	-	-	-	-
CYCLE No. FIRST DAMAGE NOTED (F):	-	-	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Recent use only - no opportunity to observe yet.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Free of smectite. A distinct difference in quality between the brown banded stone (high clay content, high porosity) and the uniform grey-white stone (high quartz content, low porosity). The brown banded stone will only be suitable for low stress situations (eg, domestic use). However, the uniform grey-white stone will be suitable for moderate stress situations, and may be appropriate for some restoration applications.

REFERENCES: (1) Blake 1958

No. 29

SOURCE: Molesworth Quarry

CURRENT STONE LEASE: 984 P/M (2 ha., pegged 12/9/1977, held by J.Finlayson & G. Boon)

GRID REF. / LATITUDE; LONGITUDE: EN106603 / 42° 48' 35" S; 147° 07' 44" E

LOCATION / LAND TENURE: On a hillside east of Collins Cap Rd., off Molesworth Rd., Molesworth. (Stone is marketed at Pontville showroom, under name of "Pontville Freestone".)

KNOWN USAGE: Flagging stone.

DATE(S)	USE
~1965 - present	Mainly domestic use in Hobart; ornamental feature walls and paving.
~late 1960's	Schweppes Building, 76 Federal St., N. Hobart
1989	Domestic residence (G.Britton), Smithton

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Accessable and currently worked. Quarry approx. 200m long (N-S) with main face 10 - 15 metres high. Situated on a steep hillside. Significant accessible reserves available, although face is quite high.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 050 / FB 1^{*};

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic Quartz Sandstone Sequence, Rls (1) (2). Dolerite contacts sandstone on an intrusive contact ~300 metres to the west.

JOINTING / FRACTURING: Major normal fault outcrops in middle of quarry, striking approx. E - W, with south side downthrown 2 - 3 metres. Otherwise, numerous sub-vertical joints trending in several directions are spaced 1 - 3 metres apart. Joints have been a major pathway for iron-oxide bearing waters, and control quarry development.

BEDDING: Dip 5° towards 225° True. Plane bedded. Stone splits easily into slabs ~0.02 - 0.1 m thick, becoming thicker towards top of quarry.

COLOUR (FRESH, DRY): Very light grey (N8) to very pale orange (10 YR 8/2) GRAINSIZE: Medium SORTING: Moderate

COHERENCE: Coherent HOMOGENEITY: Uniform, homogeneous stone.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Strong, attractive brown iron oxide staining abundant, as joint-controlled Liesegang rings, dendrites, and other mottlings. Less iron oxide colouration towards top of face, and in the central parts of large (1 - 3m wide) joint blocks, which can be a uniform unpatterned grey-white colour.

PHYSICAL PROPERTIES		SPECIMENS
		FB 1 [*]
EFFECTIVE POROSITY	(vol.%)	8.97
WATER ABSORPTION	(wt.%)	4.13
DRY BULK ROCK DENSITY	(t/cubic metre)	2.17
DRY POINT LOAD	Av. all directions	2.11
STRENGTH INDEX (MPa)	Av. normal to bedding	2.09
	Av. parallel to bedding	2.14
ULTRASONIC	Av. all directions	3262
PULSE VELOCITY (m/sec)	Av. normal to bedding	-
	Av. parallel to bedding	-
MINERALOGY		
QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" " ")	23
CLAY TYPES (vol.% of total clay)		
SMECTITE or ILLITE/SMECTITE mixed layer		-
ILLITE		55
KAOLINITE		45
VERMICULITE		-
CHLORITE		-
HALITE		-
GYPSUM		-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST		
VOLUME % LOSS, 10 CYCLES	(V):	7
CYCLE No. FIRST DAMAGE NOTED	(F):	8

OBSERVED DURABILITY OF STONE IN BUILDINGS: Good; no decay seen in Hobart feature walls in which this stone has been used.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Very low porosity, high strength and UPV, absence of smectite and good result in salt test indicate good durability in both high and low stress situations.

REFERENCES: (1) Leaman 1972 (2) Leaman 1976

No. 30

SOURCE: Mike Howes Marsh Quarry

CURRENT STONE LEASE: 1189 P/M (4 ha., pegged 22/1/1985, held by G.N. Howard, Bond St., Ross ["Unique Stone Paving", Oatlands])
 GRID REF. / LATITUDE; LONGITUDE: EP 236239 / 42° 14' 10" S; 147° 17' 11" E
 LOCATION / LAND TENURE: Approx. 10 km NW of Oatlands, near Interlaken Rd, on "Mormiston" property.
 KNOWN USAGE: Flagging stone.

DATE(S)	USE
1985 - present	Worked by Unique Stone Paving, as ornamental paving and cladding, including: Recent use to build house in Ross ("bookleaf" wall construction) Tasmanian use, export to mainland.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Access from Oatlands via Interlaken Rd. and private road. Currently worked over 150 x 150m area. Faces ~ 1.0m high. Slabs sawn *in situ*, split along bedding and lifted with forklift.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 049 / MH 1^{*};

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite, Rp (1); intrusive dolerite dyke 300 metres east of quarry, nearest mapped fault 1.5 km to east.

JOINTING / FRACTURING: Open sub-vertical joints spaced 1.0m to (dominantly) 4 or 5m apart, dominant joint set strikes 310° - 360° T.

BEDDING: Dip 6° towards 345° T. Plane bedded with possible current lineations. Regularly alternating sandstone beds 20 - 80mm thick (no internal laminations), and clay-rich micaceous sandstone beds/laminae <1.0 to 20mm thick.

COLOUR (FRESH, DRY): Very light grey (N8), but dominated by iron oxide staining. GRAINSIZE: Fine SORTING: Moderate to well sorted.

COHERENCE: Sandstone beds coherent HOMOGENEITY: Homogeneous within beds/laminae.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Abundant (40-80% of stone volume) iron oxide staining (liesegang rings, spots, other patterns), coloured greyish-red (5 R 4/2) to pale reddish brown (10 R 5/4).

PHYSICAL PROPERTIES

SPECIMENS

EFFECTIVE POROSITY	(vol.%)	MH 1 [*]	10.15
WATER ABSORPTION	(wt.%)		4.47
DRY BULK ROCK DENSITY	(t/cubic metre)		2.27
DRY POINT LOAD	Av. all directions		2.46
STRENGTH INDEX	Av. normal to bedding		1.93
(MPa)	Av. parallel to bedding		2.89
ULTRASONIC	Av. all directions		3032
PULSE VELOCITY	Av. normal to bedding		2637
(m/sec)	Av. parallel to bedding		3428

MINERALOGY

QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" " ")	23
CLAY TYPES	(vol.% of total clay)	
SMECTITE or ILLITE/SMECTITE mixed layer		-
ILLITE		42
KAOLINITE		58
VERMICULITE		-
CHLORITE		-
HALITE		-
GYPNUM		-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):	4
CYCLE No. FIRST DAMAGE NOTED (F):	2

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not observed.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: The high strength, good porosity, absence of smectite and good result in salt test all indicate good durability in both high and low stress situations. Regularly interlaminated clay-rich laminae/beds not usable and must be removed from slabs.

REFERENCES: (1) Forsyth 1986, 1989

No. 31

SOURCE: Kingston Quarry

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: EN265425 / 42° 58' 08" S; 147° 19' 30" E
 LOCATION / LAND TENURE: Beside Channel Highway, 1.5 km NE of Kingston
 KNOWN USAGE: Flagging stone (ornamental slabs, mostly for domestic use).

DATE(S)	USE
-1920 - 1985	Intermittently worked, most recently by "Kingston Quarries".

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Quarry accessible and workable, although bedding dip towards working area, and presence of mudstone bands, have caused face to collapse in a number of places; possibly dangerous to work. Quarry 200(?) metres long with face 8 - 10 metres high.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 051 / KN 1* (from lower half of main face).

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite Rls (1), (2). Sandstone body is a small inlier a few hundred metres diameter surrounded by dolerite. Dolerite contact within ~100 metres of quarry.

JOINTING / FRACTURING: Several major joint directions, the two most prominent having joint surfaces dipping 61° towards 50° True, and 78° towards 205° True. Joints spaced 0.1 to >1.0m apart, with greatest intensity in beds with abundant mudstone bands.

BEDDING: Dip 10° towards 245° True. Plane-laminated bedding, breaking easily into thin slabs of varying thickness. At top of east end of face, a bed of massive sandstone lies on a large trough scoured in the underlying plane-laminated sediment.

COLOUR (FRESH, DRY): Bulk colour greenish-white (or "yellowish-grey" 5 Y 8/1) GRAINSIZE: Fine SORTING: moderate/well

COHERENCE: Very coherent HOMOGENEITY: Lower beds entirely sandstone, upper beds have mudstone interlayers, except at east end of quarry where massive sandstone bed occurs.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Ubiquitous brown ("greyish-orange" 10 YR 7/6) iron-oxide staining, as spots 1 - 10mm dia., patches and mottles. Black manganese oxide dendrites, and pale "bleached" spots 5 - 10mm dia. also common.

OTHER CHARACTERISTICS: The sandstone is a hornfels (baked by dolerite).

PHYSICAL PROPERTIES		SPECIMENS
		KN 1*
EFFECTIVE POROSITY	(vol.%)	10.13
WATER ABSORPTION	(wt.%)	4.04
DRY BULK ROCK DENSITY	(t/cubic metre)	2.50
DRY POINT LOAD	Av. all directions	2.23
STRENGTH INDEX (MPa)	Av. normal to bedding	1.83
	Av. parallel to bedding	2.59
ULTRASONIC	Av. all directions	2982
PULSE VELOCITY (m/sec)	Av. normal to bedding	-
	Av. parallel to bedding	-
MINERALOGY		
QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" " ")	29
CLAY TYPES	(vol.% of total clay)	
	SMECTITE or ILLITE/SMECTITE mixed layer	-
	ILLITE	present - small XRD peak (most of clay made amorphous by baking?)
	KAOLINITE	-
	VERMICULITE	-
	CHLORITE	-
	HALITE	-
	GYPSUM	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST		
VOLUME % LOSS, 10 CYCLES	(V):	-
CYCLE No. FIRST DAMAGE NOTED	(F):	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not observed

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: High strength, low porosity, absence of swelling clay and "baked" nature suggest this stone would have high durability.

REFERENCES: (1) Leaman 1972 (2) Leaman 1976 (3) Blake 1958a

No. 32

SOURCE: Bothwell Flagging Quarry

CURRENT STONE LEASE: - GRID REF. / LATITUDE; LONGITUDE: EP0407 / 42° 23' 19" S; 147° 02' 56" E
 LOCATION / LAND TENURE: Just off Lake Highway 4km east of Bothwell. Quarry owned by local council.
 KNOWN USAGE: Flagging stone (also usable as small brick-size blocks)

DATE(S)	USE
Historic - recent	Used in many Bothwell buildings and homes ("bookdeal" style walls)
Post - 1894	Identical stone used in a balustrade in Franklin Square Public Offices, Hobart (building "L", between Deeds Building and main offices, Ref. 1). Most likely to be from this source, as no other known quarry has similar stone.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Accessible and workable (used intermittently). Low (1-3m high) faces.

SPECIMENS: One specimen, not numbered*.

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite, Rp (2), (3). Small dolerite intrusions approx. 700m NW of quarry, large intrusive mass approx. 400m NE, and a dolerite dyke approx. 200m E. of site.

JOINTING / FRACTURING: -

BEDDING: Plane bedded, easily splitting into slabs 0.1+m thick

COLOUR (FRESH, DRY): Bulk colour white (N9) GRAINSIZE: Fine SORTING: Moderate/well sorted

COHERENCE: Coherent HOMOGENEITY: Homogeneous apart from minor flat clay pellets ~10mm dia.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Stone appearance dominated by uniform scattering of medium-coarse size iron oxide spots and oval patches up to several cm long, elongated along bedding (colour moderate greyish-red 5 R 5/2).

PHYSICAL PROPERTIES		SPECIMEN
		(un-numbered*)
EFFECTIVE POROSITY	(vol.%)	8.94
WATER ABSORPTION	(wt.%)	-
DRY BULK ROCK DENSITY	(t/cubic metre)	-
DRY POINT LOAD	Av. all directions	1.98
STRENGTH INDEX (MPa)	Av. normal to bedding	-
	Av. parallel to bedding	-
ULTRASONIC	Av. all directions	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	-
	Av. parallel to bedding	-
MINERALOGY		
QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" " ")	-
CLAY TYPES	(vol.% of total clay)	
	SMECTITE or ILLITE/SMECTITE mixed layer	1
	ILLITE	26
	KAOLINITE	73
	VERMICULITE	-
	CHLORITE	-
	HALITE	-
	GYPNUM	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST		
VOLUME % LOSS, 10 CYCLES	(V):	-
CYCLE No. FIRST DAMAGE NOTED	(F):	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not observed.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: High strength, low porosity and negligible swelling clay indicate good durability for this stone.

REFERENCES: (1) Sharples 1985b (2) Forsyth *et al.* 1976 (3) Forsyth 1984

No. 33

SOURCE: Campania Quarry

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: EN336763 / 42° 39' 52" S; 147° 24' 36" E
 LOCATION / LAND TENURE: Nowra Angora Stud, just west of Campania
 KNOWN USAGE: Dimension Stone

DATE(S)	USE
Historic	? (Original Customs House, Hobart (now Parliament House) part-built 1836 with Campania stone (1), (2), (5); uncertain whether this or another local quarry used.)
~1967	Minor use by Rizzolo Stone & Concrete Pty Ltd

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Small quarry approx. 30 metres diameter with main face 3 metres high. Visible pick-hewn face indicates historic use. Easy access.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 028 / Cam 1 +

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite Riq (4). Intrusive dolente contact along pre-existing fault approx. 300m away. Post-intrusion movement on fault.

JOINTING / FRACTURING: Three joint sets present, spacing 1 - 6 metres. Common iron oxide deposits on joint surfaces. Superficial polygonal "elephant skin" fracturing on natural outcrop surfaces.

BEDDING: Dip 6° towards 169° True. Stone is massive with few clearly defined bedding planes.

COLOUR (FRESH, DRY): Bulk colour white (N9) to orange-speckled pale yellowish-orange (10 YR 8/4) GRAINSIZE: Fine-medium

SORTING: Moderate COHERENCE: Moderate to coherent HOMOGENEITY: Homogenous, free of pebbles or clay pellets.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Distinct, fine Liesegang rings ubiquitous, coloured yellowish-orange (10 YR 7/6).

PHYSICAL PROPERTIES

SPECIMENS

EFFECTIVE POROSITY	(vol.%)	Cam 1 +
WATER ABSORPTION	(wt.%)	12.80
DRY BULK ROCK DENSITY	(t/cubic metre)	5.65
		2.27
DRY POINT LOAD	Av. all directions	0.31
STRENGTH INDEX	Av. normal to bedding	-
(MPa)	Av. parallel to bedding	-
ULTRASONIC	Av. all directions	2121
PULSE VELOCITY	Av. normal to bedding	-
(m/sec)	Av. parallel to bedding	-

MINERALOGY

QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" ")	19
CLAY TYPES	(vol.% of total clay)	
SMECTITE or ILLITE/SMECTITE mixed layer		3
ILLITE		20
KAOLINITE		77
VERMICULITE		-
CHLORITE		-
HALITE		-
GYPSUM		-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):	14
CYCLE No. FIRST DAMAGE NOTED (F):	4

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not observed.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Low strength, presence of smectite, and poor salt test result suggests moderate to poor durability.

REFERENCES: (1) Twelvetreves - date uncertain (2) Spry 1983 (3) Sprod 1977 (4) Leaman *et al.* 1975 (5) Beattie - date uncertain.

No. 34

SOURCE: Melton Mowbray Quarry

CURRENT STONE LEASE: 990 P/M (1 ha., pegged 2/4/1978, held by C.L. Batt)

GRID REF. / LATITUDE; LONGITUDE: EN153979 / 42° 28' 22" S; 147° 11' 11" E

LOCATION / LAND TENURE: On "Woodlands" property of Mr Charles Batt MLC, on ridge north of homestead, east of Melton Mowbray pub. Identical stone outcrops in Midlands Highway road-cutting immediately adjacent.

KNOWN USAGE: Dimension Stone.

DATE(S)	USE
Historic	"Woodlands" Homestead)
"	Melton Mowbray Pub) Stone from nearby excavation adjacent Woodlands Homestead (1).
"	Kempton Post Office)
1922	War Memorial Clock Arch, Kempton)
Modern	Use by Etna Stone Pty. Ltd. of quarry described here includes:
1979	St. Davids Cathedral, Hobart (restoration works)
	Not currently worked.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Easy access. Small working 10 metres diameter, face 0.5m high.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): Quarry: G 400 042 / MM 1*; Highway Roadcutting: 24/1/1*; 24/1/2*

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite: Rp, just below Rm (2). Nearest mapped dolomite outcrops 1 - 1.5km distant.

JOINTING / FRACTURING: Random fractures 1 - 2 m apart in quarry, joints very widely spaced (5m+) in road cutting.

BEDDING: Dip 6° towards 354° True. Crossbedded sandstone, laminations commonly distinct: dark, mica-rich, easy-splitting.

COLOUR (FRESH, DRY): Moderate yellowish-brown (10 YR 5/4) GRAINSIZE: Fine SORTING: Moderate/well

COHERENCE: Moderate HOMOGENEITY: No pebbles or clay pellets, but bedding laminations commonly distinct and mica-rich.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Colour essentially uniform with no banding or other patterning apart from presence of scattered minor indistinct dark spots up to 8mm dia. (Iron or manganese oxide).

PHYSICAL PROPERTIES		SPECIMENS		
		MM 1*	24/1/1*	24/1/2*
EFFECTIVE POROSITY	(vol.%)	14.81	18.07	15.87
WATER ABSORPTION	(wt.%)	6.87	6.95	7.77
DRY BULK ROCK DENSITY	(Vcubic metre)	2.13	2.31	2.04
DRY POINT LOAD	Av. all directions	1.51	0.49	0.62
STRENGTH INDEX (MPa)	Av. normal to bedding	-	-	-
	Av. parallel to bedding	-	-	-
ULTRASONIC	Av. all directions	2808	-	-
PULSE VELOCITY (m/sec)	Av. normal to bedding	-	-	-
	Av. parallel to bedding	-	-	-
MINERALOGY				
QUARTZ	(vol.% of total mineral matter)	-	-	-
TOTAL CLAY	(" " ")	23	-	-
CLAY TYPES (vol.% of total clay)				
	SMECTITE or ILLITE/SMECTITE mixed layer	-	-	-
	ILLITE	87	40	32
	KAOLINITE	-	14	25
	VERMICULITE	13	46	43
	CHLORITE	-	-	-
	HALITE	-	-	-
	GYPSUM	-	-	-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST			
VOLUME % LOSS, 10 CYCLES (V):	16	-	-
CYCLE No. FIRST DAMAGE NOTED (F):	5	-	-

OBSERVED DURABILITY OF STONE IN BUILDINGS: Moderate; "Woodlands" generally in good condition, but with some rounding and crumbling surfaces on east side. Clock arch in excellent condition (helped by regular cleaning?). Crumbling cavities have formed at base of quarry face itself, due to rising damp.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: High porosity and variable strength indicate susceptibility to damp and salt-related decay. Bedding laminations are also a significant weakness, although in other respects stone would perform adequately in low stress applications.

REFERENCES: (1) Charles Batt, *Pers. Comm.* 1984 (2) Forsyth *et al.* 1976 (3) Spry 1982, 1983

REFERENCES:

No. 36

SOURCE: Braemar Quarry

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: EQ395035 / 41° 31' 10" S; 147° 28' 22" E
 LOCATION / LAND TENURE: Near Blessington, NE Tasmania. Probably close to bold outcrops adjacent Braemar Creek (Gnd ref. as above).
 KNOWN USAGE: Dimension stone.

DATE(S)
1984

USE
Minor use by Dunn Monumental Masons Pty Ltd

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Not visited. Bold outcrops noted in area.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 045 / Br 1*

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Probably Early Triassic "Knocklofty Sandstone & Shale" (2), which is Unit 2 - "Quartz Sandstone Sequence" of (3).

JOINTING / FRACTURING: Widely jointed judging from nearby bold outcrops?

BEDDING: Appears massively bedded, with a few slightly darker bands 3 - 20mm thick.

COLOUR (FRESH, DRY): Light olive yellowish-grey (5 Y 6/2) GRAINSIZE: Fine - medium SORTING: Moderate

COHERENCE. Coherent HOMOGENEITY: Minor (~1%) randomly distributed dark green clay pellets av. 1-2 mm thick x 10mm dia. Minor black (?manganese oxide) spots 1-2mm dia.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Minor pale red-brown iron oxide Liesegang rings.

PHYSICAL PROPERTIES

SPECIMENS

		Br 1*
EFFECTIVE POROSITY	(vol.%)	13.04
WATER ABSORPTION	(wt.%)	5.45
DRY BULK ROCK DENSITY	(t/cubic metre)	2.39
DRY POINT LOAD	Av. all directions	0.4
STRENGTH INDEX (MPa)	Av. normal to bedding	-
	Av. parallel to bedding	-
ULTRASONIC	Av. all directions	2022
PULSE VELOCITY (m/sec)	Av. normal to bedding	1893
	Av. parallel to bedding	2156

MINERALOGY

QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" " ")	18
CLAY TYPES	(vol.% of total clay)	
	SMECTITE or ILLITE/SMECTITE mixed layer	-
	ILLITE	4
	KAOLINITE	67
	VERMICULITE	29
	CHLORITE	-
HALITE		-
GYPNUM		-

SODIUM CHLORIDE SALT CRYSTALLISATION TEST

VOLUME % LOSS, 10 CYCLES (V):	10
CYCLE No. FIRST DAMAGE NOTED (F):	2

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not observed.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Low strength, high porosity and mediocre salt test result indicate that this stone will be of moderate to poor durability, and susceptible to salt attack.

REFERENCES: (1) Spry 1983 (2) Blake 1959 (3) Forsyth in Burrett & Martin 1989

No. 37

SOURCE: Connerville Quarry

CURRENT STONE LEASE: Not current GRID REF. / LATITUDE; LONGITUDE: ?
 LOCATION / LAND TENURE: Outcrop on NW slope of Mitford Hills, north of Millers Bluff? Near Cressy, on "Connerville" property.
 KNOWN USAGE: Large slabs, ?dimension stone.

DATE(S)	USE
1950's	Gravestone, Cressy cemetery.
1983	Minor use by Dunn Monumental Masons Pty Ltd.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Not visited, due to landowner's hostility to Mines Dept.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 048 / Con 1*

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Possibly Permian?

JOINTING / FRACTURING: ?

BEDDING: Planar bedding, splits in slabs 3 - 60mm thick.

COLOUR (FRESH, DRY): Light olive-grey (5 Y 7/1) GRAINSIZE: Medium SORTING: Moderate/well

COHERENCE: Coherent HOMOGENEITY: Minor mudstone bands.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Minor orange-brown iron oxide bands and patches.

OTHER CHARACTERISTICS: Minor mica, up to 10% feldspar, and a few small (<1mm dia.) unidentified brown grains.

PHYSICAL PROPERTIES		SPECIMENS
		Con 1*
EFFECTIVE POROSITY	(vol.%)	9.07
WATER ABSORPTION	(wt.%)	3.80
DRY BULK ROCK DENSITY	(t/cubic metre)	2.39
DRY POINT LOAD	Av. all directions	1.75
STRENGTH INDEX (MPa)	Av. normal to bedding	0.76
	Av. parallel to bedding	2.88
ULTRASONIC	Av. all directions	2552
PULSE VELOCITY (m/sec)	Av. normal to bedding	2198
	Av. parallel to bedding	2903
MINERALOGY		
QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" " ")	30
CLAY TYPES	(vol.% of total clay)	
	SMECTITE or ILLITE/SMECTITE mixed layer	-
	ILLITE	79
	KAOLINITE	21
	VERMICULITE	-
	CHLORITE	-
	HALITE	-
	GYPSUM	-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST		
VOLUME % LOSS, 10 CYCLES	(V):	5
CYCLE No. FIRST DAMAGE NOTED	(F):	5

OBSERVED DURABILITY OF STONE IN BUILDINGS: Good durability observed on Cressy gravestone exposed to frosts and wide temperature fluctuations.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: The very low porosity, moderate to high strength, absence of swelling clay, and good result in salt test indicate good durability. However, the use of this stone is limited to slabs, due to distinct planar bedding.

REFERENCES:

No. 38

SOURCE: Lachlan Quarry

CURRENT STONE LEASE: Not Current GRID REF. / LATITUDE; LONGITUDE: EN072576 / 42° 50' 00"S; 147° 05' 18"E
 LOCATION / LAND TENURE: Lachlan area, access via 1 km. 4WD track turning east off Ringwood Rd. Quarry on west flanks of "The Backbone".
 KNOWN USAGE: Flagging stone.

DATE(S) USE
 1970's - early 1980's Used by Etna Stone Pty Ltd for ornamental slabs.

QUARRY DESCRIPTION, ACCESSIBILITY, WORKABILITY: Worked intermittently. Access by 4WD track, quarry is on a steep slope, awkward to work. Quarry face approx. 50 metres long, 5 metres high.

SPECIMENS (DEPT. OF MINES No. / FIELD No.): G 400 043 / Lach 1*

STRATIGRAPHY / GEOLOGICAL ENVIRONMENT: Early Triassic quartz arenite, Ris (1), (2). Intrusive dolerite contact within 100 metres horizontally.

JOINTING / FRACTURING: Primary joint set dips 65° towards 154° True. Joint spacing 1 - 2 metres.

BEDDING: Dip 5° towards 324° True. Plane laminated bedding, splits easily into slabs approx. 0.1 metres thick. Low angle planar or wedge-shaped cross-bed sets appear in places.

COLOUR (FRESH, DRY): Bulk colour greyish-white to greyish-orange (10 YR 7/4) GRAINSIZE: Fine SORTING: Moderate

COHERENCE: Moderate HOMOGENEITY: Homogeneous.

DIAGENETIC/WEATHERING COLOURATION/EFFECTS: Ubiquitous strong brown iron oxide patterning, as Liesegang rings, mottles, patches.

PHYSICAL PROPERTIES		SPECIMENS
		Lach 1*
EFFECTIVE POROSITY	(vol.%)	9.70
WATER ABSORPTION	(wt.%)	4.54
DRY BULK ROCK DENSITY	(t/cubic metre)	2.13
DRY POINT LOAD	Av. all directions	0.98
STRENGTH INDEX (MPa)	Av. normal to bedding	-
	Av. parallel to bedding	-
ULTRASONIC	Av. all directions	3006
PULSE VELOCITY (m/sec)	Av. normal to bedding	-
	Av. parallel to bedding	-
MINERALOGY		
QUARTZ	(vol.% of total mineral matter)	-
TOTAL CLAY	(" " ")	26
CLAY TYPES (vol.% of total clay)		
SMECTITE or ILLITE/SMECTITE mixed layer		-
ILLITE		51
KAOLINITE		49
VERMICULITE		-
CHLORITE		-
HALITE		-
GYPSUM		-
SODIUM CHLORIDE SALT CRYSTALLISATION TEST		
VOLUME % LOSS, 10 CYCLES	(V):	10
CYCLE No. FIRST DAMAGE NOTED	(F):	3

OBSERVED DURABILITY OF STONE IN BUILDINGS: Not observed.

GENERAL ASSESSMENT OF QUALITY, DURABILITY AND VARIABILITY: Good durability indicated by measured properties.

REFERENCES: (1) Leaman 1972 (2) Leaman 1976 (3) Spry 1983

APPENDIX TWO

SPECIMEN CATALOGUE

The following is a list of representative samples studied during this project and submitted to accompany this thesis (see Appendix One for details of specimens).

Hand specimens are housed at the Tasmanian Department of Mines ("D.O.M.", now Dept. of Resources & Energy, Division of Mines).

Thin sections are housed in the collection of the Geology Department, University of Tasmania (UTGD).

In many cases, the same specimen has both a D.O.M. and a UTGD number, due to this separation of the two collections.

Hand specimen collection, Department of Mines

D.O.M. Number	Field No.	Source
G 400 001	PA 1	(1) Port Arthur - Plummers Quarry
2	PA 4	(2) Port Arthur - Palmers Lookout Road Quarry
3	PA 5	(2) " " " "
4	PA 2	(3) Port Arthur - Safety Cove Quarry
5	PA 3	(3) " " " "
6	V 1	(12) Ventenat Point, Bruny Island
7	V 2	(12) " " " "
8	V 3	(12) " " " "
9	SM 1	(4) Kangaroo Point Green Stone
10	MHQ 1	(5) Kangaroo Point White Stone
G 400 011	TT 3	(13) Tea Tree Quarry
12	TT 4	(13) " " "
13	TT 5	(13) " " "
14	TT 6	(13) " " "
15	TT 7	(13) " " "
16	TT 8	(13) " " "
17	LPO 3	(13) " " " (Launceston G.P.O.)
18	LPO 4	(13) " " " "
19	Ross 1	(16) Ross Quarry A
20	Ross 2	(16) " " "
G 400 021	Ross 3	(16) " " "
22	Ross 6	(16) Ross Quarry B
23	Ross 7	(16) Ross Quarry C
24	Ross 4	(16) Ross Quarry D
25	Ross 5	(16) " " "
26	Oak 1	(14) Okehampton Quarry, east working
27	Oak 2	(14) Okehampton Quarry, west working
28	Cam 1	(33) Campania
29	WW 1	(9) Waterworks
30	TR1	(7) Domain Quarries
G 400 031	TR 2	(7) " " (mudstone; deleted from App. 1)
32	K 1	(8) Knocklofty Quarry (" " ")
33	K 2	(8) " " "
34	OC 1	(19) Ouse Lithic Sandstone
35	L 1	(27) Linden Quarry
36	L 2	(27) " " "
37	Riz 1	(24) Oatlands Quarry
38	Etna 1	(21) Pontville Brown Stone Quarry
39	Etna 2	(21) " " " "
40	Etna 3	(22) Pontville White Stone Quarry
G 400 041	Cobb 1	(23) Cobbs Hill Quarry
42	MM 1	(34) Melton Mowbray Quarry
43	Lach 1	(38) Lachlan Quarry
44	N 1	(25) Nunamara Quarry
45	Br 1	(36) Braemar Quarry
46	Cop 1	(35) Copping Quarry
47	Cop 2	(35) " " "
48	Con 1	(37) Connorville Quarry

D.O.M. Number	Field No.	Source
49	MH 1	(30) Mike Howes Marsh Quarry
50	FB 1	(29) Molesworth Quarry
G 400 051	KN 1	(31) Kingston Quarry

Thin section collection, Geology Dept., Uni. of Tasmania

UTGD Number	Field No.	Source
73678	PA 1	(1) Port Arthur - Plummers Quarry
9	PA 2	(3) Port Arthur - Safety Cove Quarry
73680	PA 3	(3) " "
1	PA 4	(2) Port Arthur - Palmers Lookout Rd. Quarry
2	PA 5	(2) " "
3	SM 1	(4) Kangaroo Pt. Green Sandstone Quarry
4	MD 1	(4) " "
5	M 1	(4) " "
6	MHQ 1	(5) Kangaroo Pt. White Sandstone Quarry
7	MHQ 2	(5) " "
8	Tr 1	(7) Domain Quarries
9	K 2	(8) Knocklofty Quarry
73690	WW 1	(9) Waterworks Quarries
1	V 1	(12) Ventenat Point Quarry
2	V 2	(12) " "
3	V 3	(12) " "
4	BNZ 1	(13) Tea Tree Quarry
5	TT 3	(13) " "
6	TT 4	(13) " "
7	TT 5	(13) " "
8	TT 6	(13) " "
9	TT 7	(13) " "
73700	TT 8	(13) " "
1	LPO 3	(13) " "
2	LPO 4	(13) " "
3	Oak 1	(14) Okehampton Quarry
4	Oak 2	(14) " "
5	OR 1	(15) Orford Quarry
6	Ross 1	(16) Ross Quarries
7	Ross 2	(16) " "
8	Ross 3	(16) " "
9	Ross 4	(16) " "
73710	Ross 5	(16) " "
1	Ross 6	(16) " "
2	Ross 7	(16) " "
3	Bo 2	(17) Bothwell Rifle Range Quarry
4	RR 4	(17) " "
5	OC 1	(19) Ouse Lithic Sandstone Quarry
6	Etna 1	(21) Pontville Brown Stone Quarry

UTGD Number	Field No.	Source
7	Etna 2	(21) Pontville Brown Stone Quarry
8	Etna 3	(22) Pontville White Stone Quarry
9	Cobb 1	(23) Cobbs Hill Quarry
73720	C/2/1	(23) "
1	C/3/1	(23) "
2	Cobb 2	(23) "
3	C/1/1	(23) "
4	C/1/2	(23) "
5	Riz 1	(24) Oatlands Quarry
6	N 1	(25) Nunamara Quarry
7	51/2/1	(26) Elderslie Quarry
8	51/2/7	(26) "
9	E 1	(26) "
73730	E 2	(26) "
1	E 3	(26) "
2	E 4	(26) "
3	E 5	(26) "
4	E 6	(26) "
5	E 7	(26) "
6	E 8	(26) "
7	E 9	(26) "
8	E 10	(26) "
9	E 11	(26) "
73740	L 1	(27) Linden Quarry
1	L 2	(27) "
2	S/Ts/67/1/1	(28) Buckland Quarry
3	S/Ts/67/1/2	(28) "
4	S/Ts/67/1/3	(28) "
5	S/Ts/67/1/4	(28) "
6	FB 1	(29) Molesworth Quarry
7	MH 1	(30) Mike Howes Marsh Quarry
8	KN 1	(31) Kingston Quarry
9	Cam 1	(33) Campania Quarry
73750	MM 1	(34) Melton Mowbray Quarry
1	Cop 1	(35) Copping Quarry
2	Cop 2	(35) "
3	Br 1	(36) Braemar Quarry
4	Con 1	(37) Connorville Quarry
5	Lach 1	(38) Lachlan Quarry
6	S/Ts/66/1/1	Kempton lithic sst. (EN166913); see Sect. (7.6.3 B)
7	S/Ts/66/1/2	" " "

APPENDIX THREE

SANDSTONE DATA COLLECTION AND TESTING METHODS

Those sandstone properties which are of relevance to building stone quality and durability have been described in Chapter Two, and information and speculations on their genesis have been given in Chapter Seven. This appendix describes the methods used in measuring and testing those properties. Methods of conducting salt crystallisation tests on sandstone samples are also given.

Where relevant, Australian or foreign standard test methods are quoted. In some cases the methods used in the present work have varied from the established standards; such variations are noted in the relevant places.

(A 3.1) DETERMINATION OF MINERAL CONSTITUENTS

(A 3.1.1) Clastic grains, mineral cements, clays

(A) Mineral identification - Optical Mineralogy

Standard rock thin sections of each specimen are prepared and examined under plane and polarised light using a petrographic microscope. Mineral identifications are made according to the standard methods of optical mineralogy (see, for instance, Kerr 1977).

In some cases it is difficult to identify particular minerals by optical methods. For instance, iron oxides and clays can easily be identified optically as a class of minerals (ie, as "iron oxides" or "clays"), but the particular species of iron oxides or clays present may not be determinable optically. In such cases it is necessary to proceed to further testing methods to identify the particular species present. X-Ray Diffraction (XRD) is generally the most useful such method, and is described below.

It sometimes is possible to identify different clay types microscopically, however (see Kerr 1977). The ability to do so can be a very useful tool in predicting stone durability since it is not only the clay types present which influence durability, but even more so the morphology and distribution of masses of the various clay types (see Section 2.3.4). Optical clay identification should be cross-checked by XRD

The commonest clay types are distinguished in normal thin sections as below (Kerr 1977):

Kaolinite	Pale to colourless in plane light; weak birefringence giving grey/white interference colours under crossed nicols; low relief ($n > \text{balsam}$).
Illite	Pale to colourless in plane light; strong birefringence giving bright 2nd or 3rd order interference colours under crossed nicols; low relief ($n > \text{balsam}$).
Smectite	Pale to colourless in plane light; moderate birefringence giving 2nd or 3rd order interference colours under crossed nicols; rather low relief ($n < \text{balsam}$); commonly mixed with illite.

(B) Quantitative mineralogical composition - Optical Point Counting

When the types of minerals present have been determined, their relative volumetric proportions in a sandstone can be accurately determined by optical point counting (Chayes 1949).

Point counting is described by Pettijohn *et al.* 1973,p.587 and Folk 1974. It is performed using a "Point Counter" which is attached to the stage of the petrographic microscope and moves the rock thin section by set intervals. This allows the thin section to be moved so that the eyepiece cross-hairs successively alight on a series of points on the thin section arranged in a regular grid. By identifying the mineral under the cross-hairs at each point in this grid, the proportions of various minerals present can be determined statistically after a large number of points have been counted.

In theory, porosity can also be measured by this method, using green epoxy resin to highlight pore spaces. However it is often unclear whether the holes in a thin section are true pores or simply defects produced during thin section preparation, and in addition micropores may not be identifiable. Also, this method does not take into account the existence of "porosity" due to water absorption into clay aggregates. Thus, no attempt has been made to determine porosity by point counting in this project, and holes have been left uncounted when the point counter has alighted upon them.

Due to this, mineral volume percentages quoted in this work are percentages of total mineral matter present, not percentages of total bulk stone volume.

According to Folk (1974) the interval between points counted on a thin section should be larger than the largest grains present, so that no grain is counted twice. One millimetre is usually satisfactory for sandstones. In this work, points were counted in a grid spaced 0.33mm apart in one direction and 1.0mm apart in the other. Each line of points should not run parallel to bedding as this could result in a bias if particular minerals are concentrated along particular bedding planes.

Pettijohn *et al.* (1973) says 200 - 500 grain counts (points) per thin section is standard for composition estimation. For most of the data collected in this project, 200 points per thin section were counted, although later determinations have been performed using 300 points. A 10/0.25p objective lense was used.

Pettijohn *et al.* (1973) gives a relationship for estimating the 95% confidence limits for mineral proportions obtained by the point count method. Since the majority of total clay percentages obtained in this work fell between 10 - 30%, the relationship indicates that, based on point counts of 200 counts each, the volume percentages obtained are accurate to within 4.0 to 6.5 percent.

(A 3.1.2) Clay matrix (XRD)

(A) Clay mineral identification - X- Ray Diffraction

The methods of X-Ray Diffraction (XRD) analysis used in this project are adapted from the comprehensive discussions given in Carroll (1970) and Starkey *et al.* (1984).

Sample Preparation

The method employed produces "oriented" clay mounts; that is, prepared so that the individual clay flakes will generally lie with their basal surfaces flat on the slide, in order to produce well defined XRD peaks.

Approximately 100 grams (more if possible) of sandstone is crushed as finely as possible (either by mortar and pestle or with a mechanical crusher). The resulting powder is placed in a beaker and mixed well with water so that a suspension of clay particles is produced. After allowing several minutes for the coarser particles to settle out, a small amount of the clay suspension is syphoned off with an eye-dropper or syringe and carefully placed on a clean heat-proof glass or ceramic tile appropriate to the XRD sample holder. The suspension is allowed to dry gently at room temperature (24 hours or so) on the tile, and so produces a clay mount ready for analysis.

This method produces samples adequate for routine analysis, although minor silica and feldspar will often also appear in the analysis. More rigorous methods can be used to settle the fine quartz and feldspar out of the suspension, although there does not seem to be any necessity for this.

It was found in test trials that the use of hydrogen peroxide (H_2O_2) can produce marginally larger and better defined XRD peaks than the method above, since the H_2O_2 dis-associates into H_2O and O_2 , breaking up the clay aggregates more finely in the process. However the improvement is minor, and the use of this rather time-consuming process was discontinued during this project.

The method (Müller 1967,p.38) is to place the dry sandstone powder in a beaker and just cover it with 15% H_2O_2 . The H_2O_2 is allowed to react and completely evaporate (several days). If it is not evaporated, the continuing slow reaction will produce bubbles in the clay mount. Once the H_2O_2 has evaporated, the resulting clay paste can be mixed with water and the procedure is as before.

Clay Identification

The clay mount is subjected to X-Ray diffraction analysis using a Cu tube with a Ni filter to give $\text{CuK}\alpha$ radiation. Scanning between 3° and 50° 2θ is sufficient to identify all clay minerals (and salts, etc) which may occur in sandstones, by their principal (001) peaks on the XRD diffractogram so produced.

After a normal X-Ray diffraction the clay mount is placed in a dessicator flask containing a dish of ethylene glycol. Carroll (1970) recommends placing the dessicator in an oven at 60° Celsius for at least one hour, but in fact leaving the slide in a dessicator at room temperature (20° C) for 24 hours has the same effect.

A quicker alternative method can be used when the clay mount is on a (porous) ceramic tile: the mount is simply placed over the opening of a vacuum flask and liquid ethylene glycol spread over the clay. As the liquid is sucked through the clay mount and tile into the flask,

any smectite present will expand virtually immediately.

The mount is then subjected to X-Ray diffraction again. Any smectite peaks present will have moved (normally to the 17 Angstrom position) and become more distinct due to smectite expansion with uptake of the ethylene glycol. Halloysite ($4H_2O$) also expands slightly upon glycolation.

All specimens should be routinely glycolated, since smectite sometimes cannot even be guessed at in the normal XRD diffractogram, and yet may show up strongly in the glycolated diffractogram.

Chlorite and vermiculite, which may occur in tasmanian sandstones, both give a first-order basal spacing peak at the 14 Å position, and must be heated to 550° C to be differentiated.

The technique is to place the (previously glycolated) clay mount in an oven at room temperature, heat to the required temperature, hold at that temperature for one hour, and then turn off the oven and allow to cool for four or five hours (or even overnight) without opening the oven. The sudden cooling which may result from prematurely opening the oven can cause the clay mount to crack and peel off the tile.

When the clay mount is then again subjected to XRD, a vermiculite peak will have moved from the 14 Å position to somewhere between 14 Å and 9 Å (commonly 10 Å) - vermiculite dehydrates and collapses stepwise down to 9 Å - whereas a chlorite peak will remain at 14 Å. Note that chlorite can sometimes have it's largest peak at 3.5 or 7.1 Å rather than 14 Å.

See Chapter Two (Section 2.2.4 C) regarding identification of mixed layer smectite/illite clays. Thorez (1975) gives details of other treatments which can be used to identify clay minerals in such cases that the normal, glycolated and heated XRD's still give uncertain results.

The shape of clay peaks on X-Ray diffractograms depends upon the degree of crystallinity of the clay mineral in question (Grim 1968, ch.5):

Narrow, sharp peaks (with weaker peaks present): Well ordered crystal lattices, often implying a recent authigenic clay.

Broad peaks (with weaker peaks commonly absent): Poorly ordered crystal lattices, with many defects often due to entry of impurities into the lattice through diagenesis. Often implies original detrital or early authigenic clays.

The following table indicates the diagnostic XRD peak positions for the clays most commonly found in tasmanian sandstones:

CLAY	Basal (001) peak position, Angstroms		
	NORMAL	GLYCOLATED	550° C
Illite	10	10	10 (intensified)
Kaolinite	7	7	destroyed
Smectite	12 - 15	17	10
Vermiculite	14	14	10
Chlorite	14	14	14
Halloysite ($4H_2O$)	10	11	destroyed

Table (A 3.1) Normal behaviour of common clays with various diagnostic XRD treatments.

(B) Quantitative clay mineral estimation

Relative Proportions

Some workers (eg, Green & Woolley 1981, Spry 1983) have declined to attempt quantitative determinations of the relative proportions of clay types present in a sandstone matrix, beyond simply referring to clay types as being "dominant", "sub-dominant", "present", and so on, depending on the approximate relative sizes of each clay's XRD peaks.

However, it is possible to obtain a useful estimate of relative quantities of the various clay minerals represented in an XRD diffractogram by comparing peak areas for the principal (001) peak of each mineral. The method assumes that the mass co-efficients and degree of crystal lattice ordering in the minerals are similar. The method can be accurate to within 5-10% if these conditions are fulfilled (Carroll 1970).

When smectite is present, it is preferable to perform the procedure on a glycolated diffractogram. Glycolation adds to the apparent smectite peak area, to the extent that whilst sometimes the presence of smectite is not apparent in a normal diffractogram, it will become apparent after glycolation. The method of weighting peak areas to calculate relative clay type proportions, as described below, takes into account this apparent increase in smectite peak size with glycolation.

Although peak height can be measured for a rough estimate of relative proportions, heights may vary over several runs of the same clay mount. It is better practice to measure peak areas since the latter tend to remain constant even if peak heights vary a little.

Area under the peak (above the background radiation trace) can be simply measured and calculated if the peak shape approximates an isocles triangle, or else a polar planimeter can be used.

The areas obtained are arithmetically converted to percentages of the total area under all the principal clay peaks, yielding percentages of the total clay content of the sandstone. However, the peak areas of different clays are not all comparable on a 1:1 proportional basis. The areas obtained under each peak must be weighted before converting to a percentage of the total clay matrix:

- The illite peak area must be multiplied by 4 to be directly comparable to the smectite peak after glycolation, according to Johns *et al.* 1954, *in* Starkey *et al.* 1984.
- Peak areas for illite and kaolinite are comparable on a 1:1 basis provided neither is very well crystallised or ordered (ie, when their peaks are broad). However, when the kaolinite is well crystallised (high narrow peaks) then the kaolinite peak area is double that of the equivalent amount of illite, according to Schultz 1960, *in* Starkey *et al.* 1984.
- Peak areas of well crystallised kaolinites are double those of the equivalent amount of chlorite, according to Elverhoi & Ronningsland 1978, *in* Starkey *et al.* 1984.

The following table sets out the adjustments which must be made to measured principal peak areas in order to make them directly comparable. Illite is taken as standard and other clay peak areas adjusted with respect to illite:

	illite	smectite	kaolinite (disordered)	kaolinite (ordered)	chlorite
multiplication factor to make peak areas comparable.	x 1.0	x 0.25	x 1.0	x 0.5	x 1.0
(vermiculite: no data, assumed x 1.0)					

Table (A 3.2) Weighting of measured principal XRD peak areas (glycolated) required to allow direct comparison of proportions of different clays in a single clay mount.

Since all the clay minerals listed above have similar and over-lapping ranges of specific gravity, the relative percentages obtained for the various clays in the total clay matrix of a sandstone can be regarded as approximate percentages of both weight and volume.

Attempts during this project to test these proportional weighting adjustments by running XRD diffractograms of prepared combinations of known clay standards have met with only limited success, partly due to impurities in the available clay "standards", and probably partly due to variations in the degree of clay crystallinity (ordering). Since such ordering variations are likely to cover a broad range in any sandstone specimen, and can only be roughly estimated from peak shapes, the above adjustment factors must be treated as rough adjustments only.

Thus, accuracies of 5 - 10% in relative clay proportion estimates may not be obtainable in practice without more sophisticated procedures beyond the scope of the present project (see for instance Johnson *et al.* 1985).

Nonetheless, despite the probable large inaccuracies inherent in the methods described above, the percentage figures obtained are considered by the writer to be expedient for rough comparative purposes.

Absolute Proportions

Although relative XRD peak areas are proportional to the percentage of the total clay matrix in a specimen which each clay type comprises, the XRD method alone gives us no indication of absolute clay proportions as a percentage of the entire sandstone itself.

The method used in this project to obtain absolute proportions of various clay minerals in a sandstone specimen as a whole relies on preparation of a thin section slide from the same sample which the corresponding XRD analysis is performed on.

The total volume percentage of the specimen which is taken up by the clay matrix can then be easily determined by microscopic Point Counting as described in section (A 3.1.1) above. Clay is easily discernable in thin sections (although identification of particular clay types is often difficult to perform microscopically).

An alternative method of measuring total clay percentage of a sandstone relies on determining the clay size fraction of a sample by dis-aggregating (crushing) the sandstone thoroughly, mixing with water, and measuring the proportions of material which settle out after given intervals, in accordance with Stokes Law. This method allows one to determine the percentage of material present with a grain size of less than two microns, which is the "clay fraction".

In several tests it was found that this sedimentation method gives a lower clay percentage than does point counting a thin section of the same specimen. There are two likely causes of

this difference:

- 1) It is likely that disaggregation will not be entirely complete, so that some clay will remain bonded to quartz grains, or in aggregates larger than 2 microns diameter. Such bonded clay will settle out prior to the < 2 microns fraction and thus not be counted as "clay".
- 2) In microscopic determination of clay percentages, one is likely to be counting some sericite ("coarse clay" or fine mica having grainsizes >2 microns dia.) along with the true clay-size fraction. It will often be very difficult to microscopically define a cut-off point between true clay and fine sericite.

Since true clays and fine sericite will affect the durability of a sandstone in very similar ways, it is the present writer's opinion that the higher clay percentage figures obtained by point counting give a better indication of stone durability. Thus, point counting is the preferred method of total clay content determination.

Knowing the volume percentage of clay matrix in the whole sandstone from point counting, and the relative (volume or weight) percentages of each clay mineral in the total clay matrix itself from quantitative XRD, it is now a simple arithmetical procedure to calculate the absolute volume of each clay mineral as a percentage of the sandstone's total volume of mineral matter.

To obtain volume percentages of the total bulk volume of the sandstone (ie, including pore-spaces), the calculations must be adjusted to include pore volume in the total stone volume. Since it may be difficult to obtain accurate pore volumes by point counting, as explained in section (A 3.1.1), pore volume is best determined by water absorption testing (to be described below).

The absolute clay percentages obtained by the above methods are directly comparable between different sandstone specimens

(A 3.1.3) Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) can be used for identification of clastic grains, mineral cements and clay types by reference to their morphologies, although simple mineral identification techniques as described above are normally quite adequate. There have, however, been a few cases in this project in which the presence of certain clay minerals became apparent under SEM even though XRD has not indicated their presence.

However, the main value of SEM in the present studies has been in the elucidation of diagenetic processes in sandstones. The morphology of clay grains under SEM allows differentiation of recent authigenic clays (well-formed grain-shapes) from older authigenic or detrital clays (amorphous masses, clay balls, etc). Additionally, sequences of grain alterations and clay growths can be observed from noting cavity formation, inter-growth and over-growth relationships between the various minerals present.

Clay morphologies visible under S.E.M. are discussed in Section (7.8.3).

(A 3.2) DETERMINATION OF TEXTURAL PROPERTIES

(A 3.2.1) Grainsize and Sorting

These properties are defined in Chapter Two (Section 2.3), and were regularly determined for all specimens examined in this project. Determination is performed microscopically using a thin section of each specimen and a microscope eyepiece with a graduated scale.

It is possible to measure these properties accurately by measuring the diameter of a large number of grains using a Point Counter, and then mathematically obtaining mean grain diameters and phi (ϕ) standard deviation (= sorting).

Grainsize	Average grain diameter (mm)
Very coarse grained	1.0 - 2.0
Coarse grained	0.5 - 1.0
Medium grained	0.25 - 0.5
Fine grained	0.125 - 0.25
Very fine grained	0.0625 - 0.125

Table (A 3.3) Sandstone grainsize categories (*from* Berkman & Ryall 1976)

Sorting is determined quantitatively by calculating the ϕ standard deviation of grainsizes measured as *per* Pettijohn *et al.* (1973):

- 1) Using Point Counting technique, measure diameters of 100 random grains in a specimen, and convert diameters to phi (ϕ) values:

$$\phi = -\log_2 S \quad \text{where: } S = \text{diameter (mm)}$$

- 2) Calculate phi (ϕ) standard deviation (SD):

$$SD = \sqrt{\frac{\sum (w - \bar{w})^2}{n - 1}} \quad \text{where: } w = \phi \text{ value of each grain}$$

\bar{w} = average ϕ value over all measurements.

n = no. of measurements

The following table yields sorting classes determined according to the measured ϕ standard deviations (SD):

0.0 ϕ SD	WELL SORTED: majority of grains within a few % of other's diameters.
0.5 ϕ SD	MODERATELY SORTED: most grains within 50% of each other's diameters.
1.0 ϕ SD	POORLY SORTED: very wide grainsize variations.
2.0 ϕ SD	VERY POORLY SORTED

Table (A 3.4) Sandstone grain sorting classes, in terms of ϕ standard deviations (SD).

For studies in which such quantitative detail is not required, it is acceptable to determine mean grainsize using only a few grains visually chosen as being of average size, and to visually estimate sorting using a visual comparator chart such as that given by Longiaru (1987). See Figure (A 3.1):

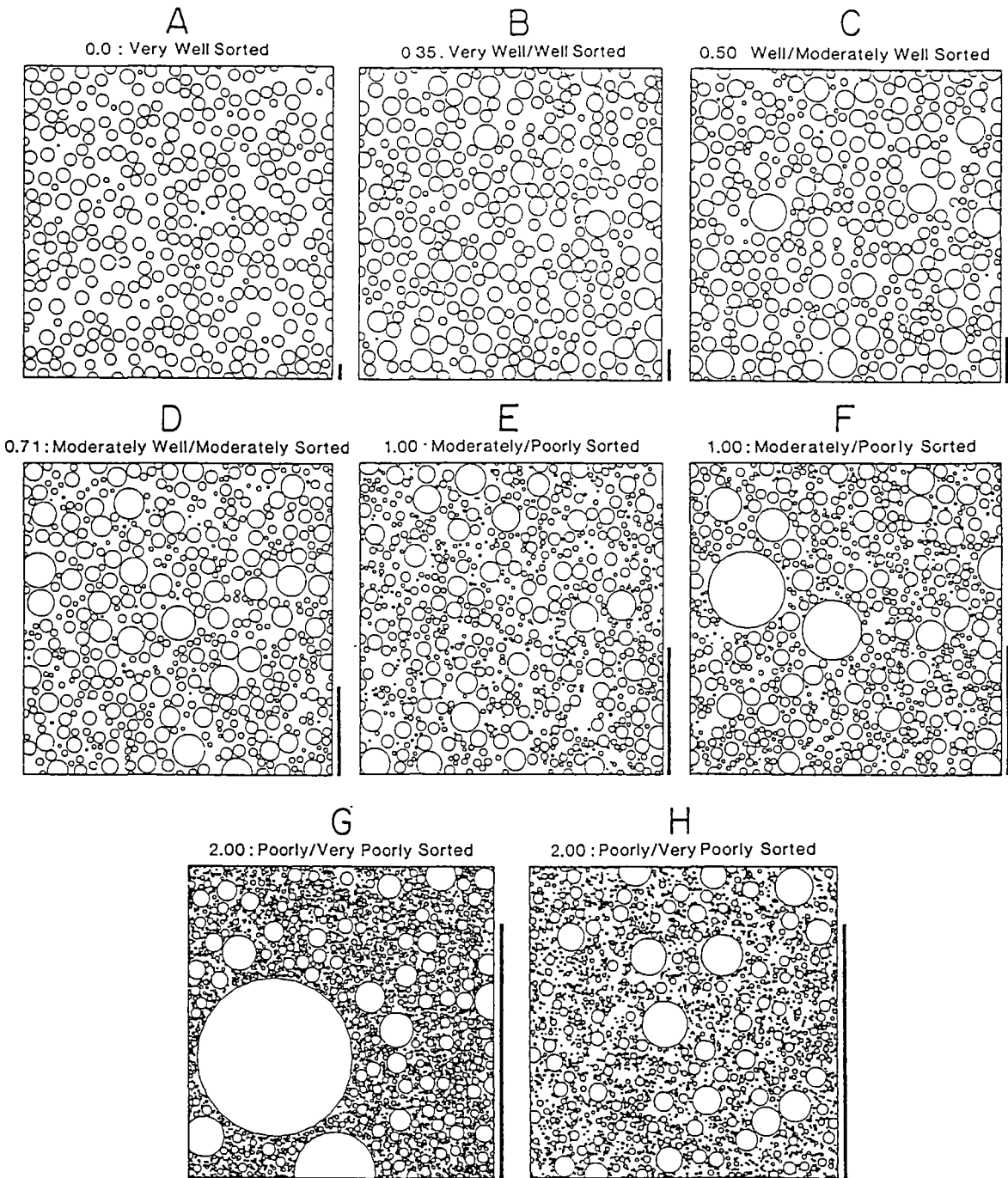


FIG. 4 —Sorting comparators. Labels indicate the degree of sorting (standard deviation) approximated by the comparator and the descriptive terminology from Folk (1966). The maximum grain size expected given a fortuitous cut through the center of the largest grain within the three-dimensional population is shown schematically as a bar at the lower right of each diagram.

Figure (A 3.1) Visual comparator chart for estimation of sandstone grain sorting. From Longiaru (1987).

(A 3.2.2) Grainshape and Orientation

Grainshape (rounding and sphericity) is also determined microscopically. Again it is possible to obtain accurate measures of these properties for detailed studies using point counting and mathematical analysis.

For less detailed studies, a quick visual estimate is normally adequate, using visual comparator charts such as that given below:

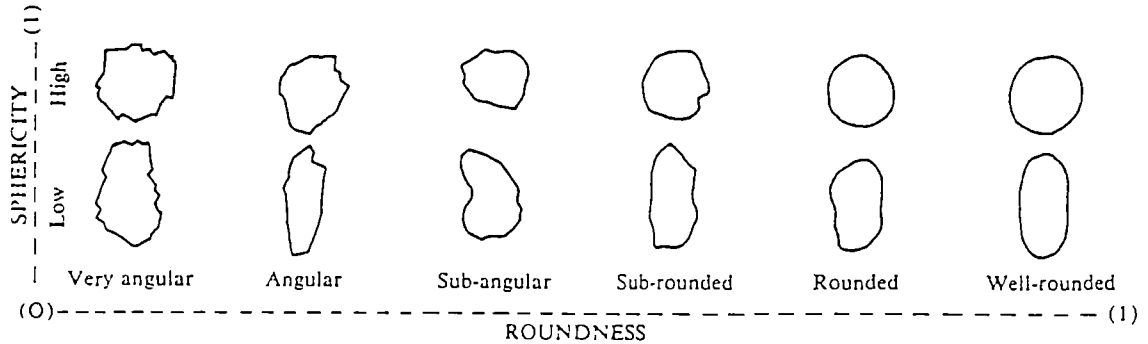


Figure (A 3.2) Visual comparator chart for determination of roundness and sphericity in sandstone grains. From Berkman & Ryall (1976).

Grain orientation is determined microscopically using thin sections cut at known angles to the bedding. Several sections cut at different angles would be needed for a proper study of grain orientation, with point counting and mathematical analysis of the data.

However, a useful indication of grain orientation can be obtained by visual estimation using a thin section cut perpendicular to bedding planes. Degree of orientation of different mineral grain types, and angle of orientation with respect to bedding, should be recorded.

(A 3.2.3) Inter-granular Texture

This textural property is very important, since it largely determines strength and porosity (see Section 7.9 & 7.10); however, it was only measured on a few samples during this project (see Section 7.11.1 and Fig. A 3.3).

Measurement of intergranular texture is carried out microscopically using a prepared thin section. Instead of Point Counting in a grid, the preferred method is to run a series of "line traverses" across the thin section slide (Kendall & Moran 1963, Erlich *et al.* 1972). The line traverses should be spaced further apart than the largest grains present. Kendall & Moran (1963, p.89-90) have shown that line traverses give accurate determinations of the relative surface areas of each grain boundary type in a unit volume of stone.

On each traverse, note is taken of each grain boundary encountered. The type of boundary contact (Quartz-Quartz (Q-Q); Quartz-Clay (Q-C); Quartz-dense Iron oxide cement (Q-Fe); or Clay-dense Iron oxide (C-Fe);) is recorded. Q-Q contact types (ie, welded or cemented; Section 2.3.4) can be difficult to differentiate in thin section.

Quartz-Clay contact types and morphologies should be recorded, since the proportion of clay present as intergranular layers or films, as opposed to interstitial masses and pellets, has a major effect on stone strength (Section 2.3.4).

Dense iron oxide cement boundaries (Q-Fe and C-Fe) can be recorded separately since the

information may be of value in attempting to determine the influence of iron oxide cements on stone strength. (Light iron oxide staining of clays is not counted as iron oxide cement, but simply as clay.)

For the purposes of this type of work, Quartz-Void, Clay-Void and Clay-Clay boundaries may be ignored when seen, since they can be very difficult to differentiate from slide imperfections in many thin sections, and moreover it is the Q-Q and Q-C contact proportions which are of primary importance.

After several hundred boundary contacts have been counted, simple mathematical analysis yields the percentages of various grain boundary contact types.

(A 3.3) DETERMINATION OF MACROSCOPIC PROPERTIES

(A 3.3.1) Coherence

As mentioned in section (2.4.1), coherence refers to the ease with which sand grains can be rubbed off fresh surfaces, and provides a rough indication of stone strength.

A friable sandstone, from which many grains can be easily rubbed off by hand, is generally weak and of low durability. A coherent stone, from which few grains can be rubbed, indicates high strength. Samples from surface outcrops are likely to be weakened, and thus less coherent, than the same stone at depth.

A useful rule of thumb is that if corners can be broken off a fresh specimen with a fingernail, then it is likely to be a weak stone.

(A 3.3.2) Colour Determination

In order to allow stone colours to be recorded in a rigorous fashion, colours are determined and classified by direct comparison with the "Rock Color Chart" prepared by, and available from, the Geological Society of America (P.O.Box 9140, Boulder, Colorado, 80401, U.S.A.).

Ideally, both wet and dry stone colours should be recorded.

The alpha-numerical colour classification system employed on the chart was developed by the Munsell Color Company (paint manufacturers), 2441 N. Calvert St., Baltimore, Maryland, 21218, U.S.A.

(A 3.3.3) Bedding, Jointing, Textural Defects

These features are described in Chapter Two, and are determined by visual inspection of outcrops.

Fresh exposures are highly desirable for proper determination of these features; examination of weathered natural outcrops can be misleading. For instance, faintly bedded stone can appear massive on weathered surfaces, visible fractures on weathered surfaces sometimes turn out to be only superficial, and surface discolouration defects may only extend a few centimetres below a natural surface.

Thus, if a weathered natural outcrop appears promising in most respects, it is essential to conduct exploratory excavations and expose fresh stone before a proper evaluation of the stone can be completed.

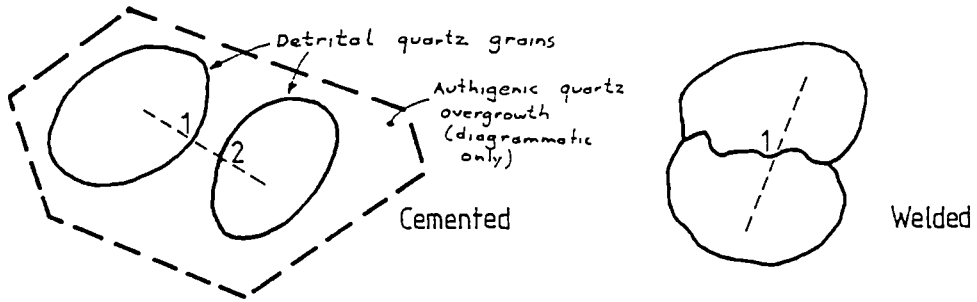
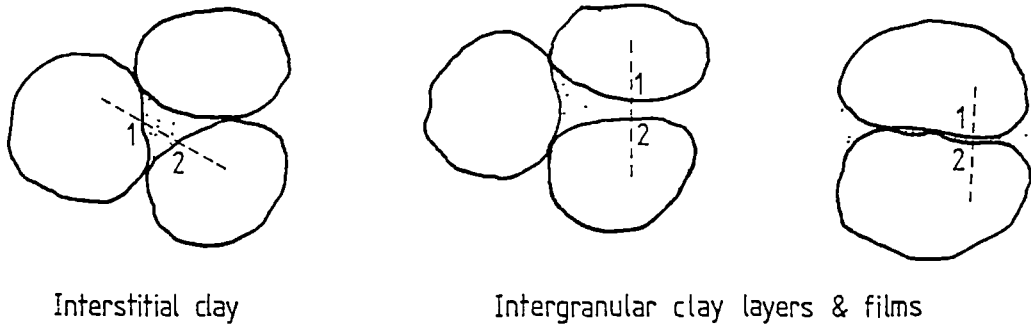
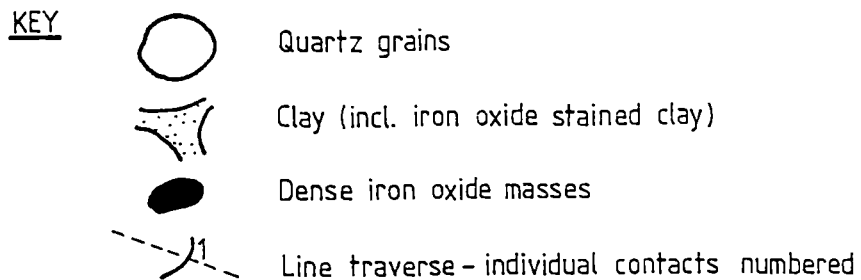
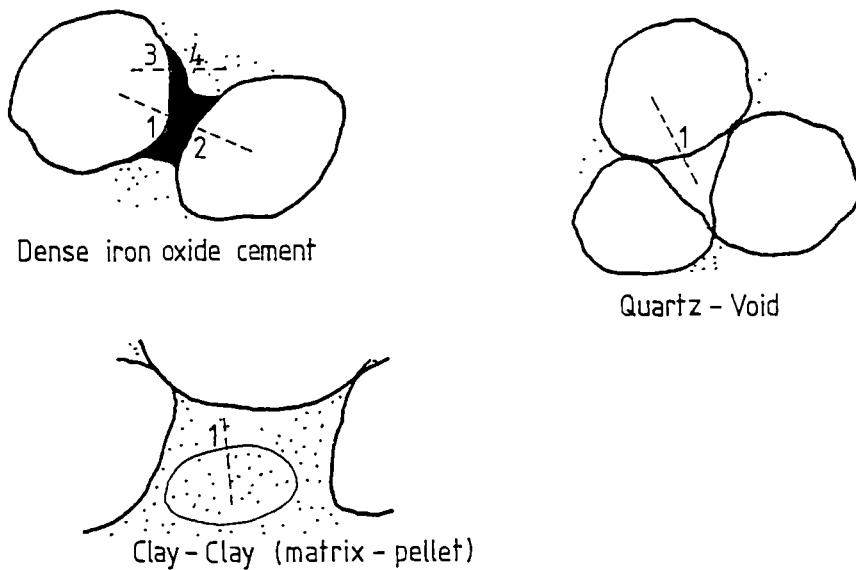
QUARTZ - QUARTZ CONTACTS:QUARTZ - CLAY CONTACTS:OTHER CONTACT TYPES:

Figure (A 3.3) Typical intergranular textures in sandstones

(A 3.4) DETERMINATION OF PHYSICAL PROPERTIES

In order to conduct reliable laboratory determinations of porosity, strength, and related physical properties, it is necessary to obtain fresh samples excavated or core-drilled from at least one metre or so below naturally weathered outcrop surfaces (see Section 7.11).

During initial exploratory investigations, it may of course be impossible to obtain anything other than surface samples. The best procedure is to locate outcrops which are good stone in other respects, and then to excavate or drill for deep samples (see Section 7.12).

(A 3.4.1) Effective Porosity, Water Absorption and Bulk Density determination

These properties are discussed in sections (2.5.1) and (2.5.2).

Standard methods for measuring these properties are given in the American Society for Testing Minerals standard (ASTM C-97-47, 1958 standard water sorption test), Griffiths (1967, p.226), and in the Standards Association of Australia draft standard CE/12/6/4/83-20 (1983). The Australian standard involves weighing samples in water and air. Due to limitations in available equipment, a variation was employed in this study wherein the volume of specimens was determined by measuring water displacement of saturated specimens in a measuring cylinder. This variation is allowable under the Australian draft standard (see section 5.5 of Australian draft).

The method employed in this project is described below:

From each specimen, three blocks are prepared. The Australian draft standard requires sawn cubes of dimensions 50x50x50 millimetres, cut using a diamond saw (with water or water-based soluble oil coolant). However, early tests in this project demonstrated that identical results are obtained using roughly broken blocks of similar dimensions, provided that their surfaces are carefully dressed and air-blasted to remove all flakes and loose grains. Each block is labelled distinctively.

The blocks were dried at 105° C for 24 hours. The Australian draft standard recommends drying at 65° C for 48 hours, and this is preferable for future work since the higher temperature could affect clays in the stone.

Each block is then carefully weighed on an electronic balance accurate to within 0.01 grams, in order to obtain the dry weight of the specimen in air (W_d) in grams.

The blocks are then completely submerged in a container of tap water at 20° C. The time of commencement of soaking is recorded, and the blocks are soaked for 48 hours. The blocks are covered with water to a depth of about 10mm, to ensure a constant head of pressure (both temperature and pressure must be held constant to obtain the most consistent results).

After soaking each block is removed from the water, excess surface water gently removed with tissue or a sponge, and then weighed to give the weight of the saturated specimen in air (W_s) in grams.

The bulk volume of each block (V_s) in millilitres is immediately measured using graduated measuring flasks (this must be done while the blocks are still fully saturated to prevent distortion of results due to uptake of water): Two graduated 500 millilitre measuring

flasks are used. One is carefully filled with exactly 500 ml of water. The block is placed in the other flask, which is then filled to the 500ml line with water from the first flask. The volume of water remaining in the first flask is then equal to the volume of the specimen. Note that one millilitre of water at 20° C equals 1.0 cubic centimetre volume.

With this data, the following calculations are made:

Effective Porosity

Water absorbed as a volume percentage. The effective pore volume (volume of water taken up) is:

$$\text{Pore Volume} = (W_s - W_d)/d_t \quad (\text{millilitres}) \quad \text{where } d_t = \text{specific gravity of water.}$$

Since the specific gravity of water at 20° C is 1.0, the pore volume is simplified to $W_s - W_d$.

Now, effective porosity is pore volume divided by bulk volume. Thus:

$$\text{Effective Porosity} = ((W_s - W_d)/V_s) \times 100 \quad (\text{vol.}\%)$$

Water Absorption

Water absorbed as a weight percentage. Water absorption is weight of water taken up divided by dry weight of stone:

$$\text{Water Absorption} = ((W_s - W_d)/W_d) \times 100 \quad (\text{wt.}\%)$$

Bulk Density

Weight per unit volume (including pore-spaces). The dry bulk density is normally used. Dry bulk rock density equals dry weight divided by bulk volume:

$$\text{Dry Bulk Rock Density} = W_d/V_s \quad \begin{array}{l} (\text{grams/cubic centimetre}) \\ (= \text{tonnes/cubic metre}) \end{array}$$

Saturated bulk rock density is also easily calculated:

$$\text{Saturated Bulk Rock Density} = W_s/V_s \quad (\text{tonnes/cubic metre})$$

(A 3.4.2) Tensile Strength - Point Load Strength Index

This property is discussed in Section (2.5.5). The test is conducted using a Point Load test apparatus as described by Broch & Franklin (1972), Bieniawski & Franklin (1972), and Bell (1983).

The apparatus essentially consists of two conical "jaws" (platens) between which a specimen of thickness D is placed. Force is applied between the platens until the specimen fails at a loading P .

Ideally, specimens should be cores sawn into short lengths. Since measured strength depends not only on specimen thickness (diameter) D between the platens, but also upon specimen width (length) L normal to the platens, certain dimensional ratios must be adhered to:

For an axial core test (loading parallel to core axis), specimens with L/D ratios of $1/1 (\pm 0.05)$ should be used. For diametral core tests (loading normal to core axis) the distance L

between the platen contact point and the nearest free end of the core is at least $0.7 D$ where D is the core diameter (= diametral thickness between the platens) (Bieniawski & Franklin 1972). It is preferable to test at least ten core samples per specimen.

In the absence of core samples, irregular rock samples, trimmed by any convenient method, may be used. Irregular samples should have a typical diameter of approximately 50mm, and the ratio of the shortest to the longest diameter (D/L) should be between 1.0 and 1.4. At least twenty irregular lump samples per specimen should be tested (Bieniawski & Franklin 1972).

According to Bieniawski & Franklin (1972), for routine testing samples should be tested at close to their natural water content (ideally having been stored at 20°C and 50% humidity for 5-6 days prior to testing). An exhaustive test program would test specimens fully saturated (soaked in water for 48 hours), at their natural water content, and fully dried (at 65°C for 48 hours). The ratio of wet/dry strength should be calculated, since a major drop in strength when stone is wetted may indicate low durability.

Since sandstones normally exhibit strength anisotropy due to bedding, strength should be tested by loading both parallel and normal to bedding.

To conduct the test, each sample is placed between the platen jaws and the loading on the jaws gradually increased until failure occurs. (Although it seems likely that the rate at which loading is applied might affect the sample failure, no standard rate of loading appears to be specified in the literature - and indeed a standard rate would be hard to achieve with the manually operated Point Load Testing apparatus commonly used.) The platen separation (specimen thickness) D is recorded in millimetres, and the load at failure P is recorded in kiloNewtons (KN).

Since the loading applied by the platens is a compressive force, the tensile stresses are generated normal to the axis of loading:

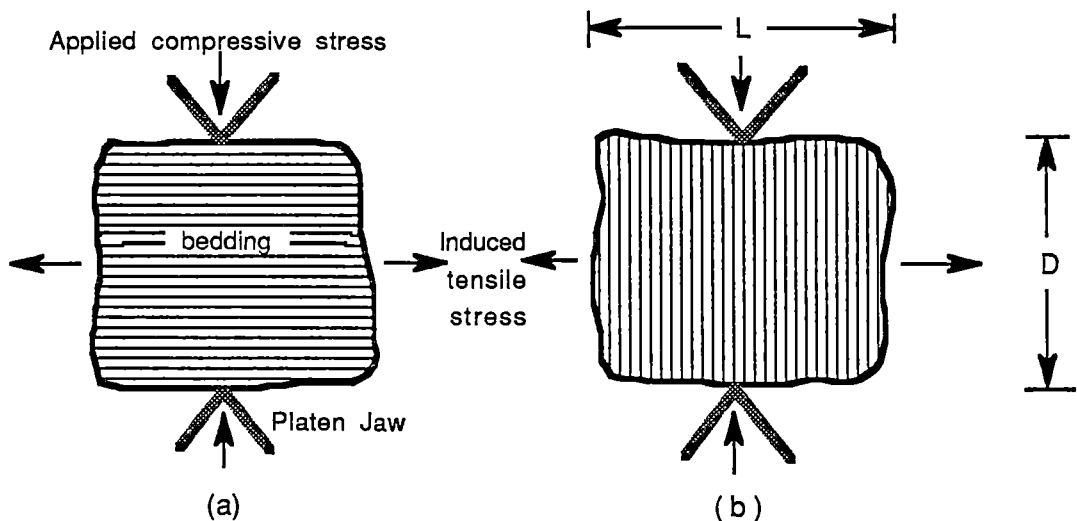


Figure (A 3.4) Measurement of Point Load Strength Index (tensile strength) parallel (a) and normal (b) to bedding.

Tensile strength is generally greater in the direction parallel to bedding, and lower normal to bedding.

In principle, the Point Load Test indirectly yields tensile strength (T) from the equation $T = 0.96 P/D^2$ (Bell 1983, p.513). However, since the actual parameter which the test directly yields is the Point Load Strength Index, it is more rigorously correct to consider only the latter:

The load (force) required to cause samples to fail by "induced tensile failure" is related to the Point Load Strength Index (Is), which is quoted in MegaPascals (MPa). In principle,

$$Is = P/D^2 \quad (\text{Bieniawski \& Franklin 1972})$$

(Since force (Newtons) is related to strength (Pascals) through the area over which the force acts.)

Since measured strength varies with sample thickness, for strength classification purposes, measured values of Is are recalculated to a standard specimen thickness of 50mm. Broch & Franklin (1972), and Bieniawski & Franklin (1972) give a set of correction curves which can be used for this calculation, but it is simpler to use the equivalent equation derived by Fitzhardinge (1978):

$$Is(50) = 140.P.(D^{-1.5}) \quad \text{MPa}$$

Where: Is(50) = Point Load Strength Index (MPa) adjusted to 50mm specimen thickness.

P = Load (force applied) at failure in KN (kiloNewtons).

D = Platen separation in millimetres.

When enough samples from each specimen have been tested both normal and parallel to bedding, the Is(50) values are calculated and tabulated separately. At this stage, Bieniawski & Franklin (1972) recommend that the median values for Is(50) normal and parallel to bedding be determined, and then the Strength Anisotropy Index Ia(50) be computed as the ratio of the two median values. [$Ia(50) = (Is(50) \text{ parallel} / Is(50) \text{ normal})$]. Ia(50) is close to 1.0 for isotropic rocks, and has higher values as anisotropy increases.

However, the procedure used in this project has simply been to separately calculate the average (not median) values for tests normal and parallel to bedding, and then to average these two results to give an averaged non-directional value for Is(50). In retrospect, this latter method is probably of less value than that proposed by Bieniawski & Franklin.

In reporting the results of Point Load Strength tests, the Is(50) values parallel and normal to bedding (both wet and dry) should be recorded, along with the number of specimens tested in each of these categories. The Strength Anisotropy Index Ia(50) (both wet and dry), and the wet/dry strength ratio (in each direction relative to bedding) should be recorded.

(A 3.4.3) Ultrasonic Pulse Velocity

Ultrasonic Pulse Velocity (UPV) is discussed in Section (2.5.7), Chapter Six and Appendix Six. Investigations undertaken during this project into the usefulness of UPV measurements in sandstone quality testing were initially reported in detail in Sharples (1985a).

The limitations and appropriate circumstances for the use of UPV measurements are detailed in the above sections of this work.

UPV is conveniently measured with the lightweight battery (or mains) powered PUNDIT instrument manufactured by C.N.S. Instruments Ltd (London).

The PUNDIT includes two transducers which are applied to flat and smooth surfaces of a specimen using a coupling agent such as vaseline, plaster, epoxy or mortar to give good acoustic coupling. One transducer generates ultrasonic pulses (at either 50 or 82 kHz) which travel through the specimen. The first arrival waves are detected by the other transducer, and the PUNDIT records the transit time T (μ -seconds). The path length L metres (shortest distance) between the transducers is measured, and the UPV can be calculated as:

$$\text{UPV} = L/T \quad (\text{metres/second}) \quad (T \text{ is converted from } \mu\text{-seconds to seconds})$$

The transmitting transducer propagates P-waves, mainly in a direction normal to the transducer face, directly through the specimen. However, a small proportion (1-2%) of the P-wave energy travels along the surface of the specimen on which the transducer rests, due to scattering of P-waves by discontinuities such as grain boundaries within the sandstone. Until the sonic energy is dissipated, first arrival waves measured on the same surface as that to which the transmitting transducer is applied will be surficially-propagated P-waves rather than slower "true" surface waves.

There are three ways of arranging PUNDIT transducer heads on a sandstone specimen. The ideal is the Direct arrangement, wherein transducers are placed on opposite sides of the specimen. This allows measurement of the maximum sonic energy being transmitted through the specimen normal to the transducer faces.

The Semi-Direct arrangement, in which the transducers are placed diagonally across from each other around a corner on the specimen, works quite well since a significant amount of sonic energy is scattered at angles of less than 90 degrees to the transducer face.

Less satisfactory is the Indirect arrangement, in which both transducer heads are placed on the same surface. This arrangement can work due to the surficial scattering of P-wave energy, but the intensity of the sonic energy is greatly reduced, and measurements of P-waves are usually unreliable. At greater path lengths probable Rayleigh waves of slower velocity are measured.

Sonic velocities are independent of the frequency of the sonic waves, as long as the least lateral dimension of the specimen (ie, the dimension normal to the direction of wave travel) is not less than the wavelength of the sonic waves (PUNDIT manual). Transducers generating 50 and 82 kHz sonic pulses are supplied with the PUNDIT. Thus, when using 50 kHz transducers a least lateral dimension of 80mm is required, and less when using 82 kHz transducers. (Note however that experimental results from this work showed that specimens several centimetres smaller than the 80mm limit give results with minimal distortion of results compared to larger specimens of the same material.)

The work conducted during this project on various Tasmanian sandstones showed that Direct and Semi-Direct mode measurements on smooth-sawn blocks can give reliable UPV measurements at path lengths up to between 0.9 and 1.2 metres. Indirect mode measurements are generally unreliable below path lengths of 0.7 to 1.0 metres. At greater path lengths (up to 1.5 metres) more consistent measurements of distinctly slower (Rayleigh?) waves are obtained.

(A 3.5) DURABILITY ASSESSMENT BY SALT CRYSTALLISATION TESTS

Inducing accelerated salt attack in sandstone specimens is a widely recognised method of assessing sandstone durability, although there is disagreement as to just what conclusions can be drawn from the test results. The tests are much harsher than conditions actually encountered in building environments, and do not duplicate all of the environmental stresses which may affect stone.

Salt crystallisation tests are best regarded as a classification of relative resistance of stone to salt attack, and the results must always be considered in conjunction with all other available data when trying to assess the durability of a sandstone.

The salt crystallisation test most commonly employed is the sodium sulphate soundness test described below (A 3.5.1). However, in the present project it was decided to experiment with a sodium chloride test which is described in (A 3.5.2) below.

(A 3.5.1) Sodium Sulphate Soundness Test (full immersion)

This is the standard salt crystallisation test for sandstone, and is fully described in the Standards Association of Australia draft standard DR 87001 (Jan. 1987). In brief, the test procedure is as follows:

- 1) Three 50mm cube samples per specimen are dried at 65° C for 48 hours, cooled for 2 hours in a dessicator, then carefully weighed to the nearest 0.1 gram (m_1).
- 2) The samples are soaked (fully immersed) in 14% decahydrate sodium sulphate solution for two hours, drained for ten minutes, dried at 65° C for 18 hours, cooled in a dessicator for two hours, then weighed to the nearest 0.1 gm and any visible changes noted.

This cycle is repeated 15 times, or until the specimen fully dis-integrates. It is preferable to photograph the samples at 0, 5, 10 and 15 cycles.

- 3) After the last cycle, samples are gently washed with clean water to remove surface salt, dried at 65° C for 18 hours, cooled in a dessicator for two hours, and weighed to the nearest 0.1 gm (m_2).
- 4) The samples are then immersed in tap water for three days (to remove additional salt), during which period the water is changed twice a day. The samples are dried at 65° C for 18 hours, cooled in a dessicator for two hours, and weighed to the nearest 0.1 gm (m_3).
- 5) The following calculations are made:

Percentage mass loss after the 15th cycle (C15):

$$C_{15} = ((m_1 - m_2)/m_1) \times 100$$

Percentage mass loss after 3-day soak (D):

$$D = ((m_1 - m_3)/m_1) \times 100$$

The cycle number at which damage first appeared is also recorded.

(A 3.5.2) Sodium Chloride Salt Crystallisation Test.

This is the (non-standard) salt crystallisation test which was employed in this project. A feature of this NaCl test is that sample decay was quantified by measuring the bulk volume loss of samples, rather than their weight loss as in the standard test above. Measuring volume loss has the advantage that it overcomes the problem that when weight is measured we are measuring not only the rock material lost from the specimen, but also the crystallised salt taken up in the pores. Even after a three day soak we cannot be sure that all salt has been flushed from the sample, so that the final weight of a specimen is probably not:

original weight - weight lost due to salt attack

but rather, is:

original weight - weight lost due to salt attack + unknown weight of salt remaining
in pores

If we measure sample bulk volumes, on the other hand, we can be sure that we are measuring purely the bulk volume of stone lost from the sample surface.

The disadvantage of measuring volumes, however, is that it is difficult to make the measurements as precise as measuring weights.

The technique of measuring sample volumes is the same as that described earlier (A 3.4.1) for measuring effective porosity.

The procedure is as follows:

- 1) Three cube samples per specimen (preferably 50 x 50 x 50 mm) are prepared, and their initial bulk volumes measured (v_1). Volumes should be measured after soaking in water for 48 hours, so that rapid water uptake during measurement does not distort the apparent bulk volume measured. The samples may then be dried at room temperature for 24 hours or more.
- 2) The samples are then subjected to ten cycles, each consisting of the following four stages:
 - a) 24 hours soaking in saturated NaCl solution at room temperature (20° C).
 - b) 24 hours heated in an oven at 90° C.
 - c) 24 hours soaking in saturated NaCl solution at room temperature.
 - d) 24 hours cooling at 4° C in a refrigerator.

At the end of each cycle, sample condition is noted. The surface of each specimen is gently washed in water, carefully dried with a sponge or tissue, and the volume is measured.

- 3) After the tenth cycle, the final volume of each sample is obtained as above (v_2). It is desirable to photograph specimens after 0, 5 and 10 cycles.
- 4) Percentage volume loss (V) over the ten cycles may now be calculated:

$$V = ((v_1 - v_2)/v_1) \times 100$$

The cycle number at which damage first appeared (F) is also noted.

APPENDIX FOUR

CHECKLIST OF REQUIREMENTS FOR HIGH QUALITY AND DURABILITY BUILDING SANDSTONE

A 4.1 INTRODUCTION

This appendix serves a two-fold purpose:

First, it is a brief checklist of sandstone properties and test results which must be assessed to determine stone quality and durability. It is hoped that such a checklist will be valuable to future workers as a brief introduction to the details of sandstone quality assessment discussed in some detail through this thesis.

Second, it also provides a list of specific values for some of those properties which can be regarded as cut-off points between high and lower quality stone. Such cut-off values have not been discussed in the body of this thesis, since no work was done by the writer towards identifying suitable cut-off values. As well, there is no complete agreement amongst workers in the field as to the most appropriate cut-off values. However, the values quoted here appear to be fairly widely accepted, subject to the provisos discussed below.

In addition, standard or draft standard methods of performing some of the tests required for stone quality evaluation are listed in Section A 4.3.

A 4.2 CRITERIA FOR HIGH QUALITY AND DURABILITY SANDSTONE

No official Australian standards for sandstone quality have yet been defined. The American Society for Testing and Materials (ASTM) lays down criteria for good building sandstone (ASTM C 616). See: ASTM Annual Standards Book (Vol. 04.08 - Soil and Rock, Building Stone).

However, unofficial Australian standards for sandstone quality have been developed from local experience, and in some respects are more stringent than those given in the above ASTM publication. See Spry (1983 & 1988) and Gere *et al.* (1989). The standards quoted in the following sections are derived from both ASTM literature, and Australian sources as referenced.

In general, the standards and criteria quoted can be considered to apply to specification of sandstone of the highest durability and quality for use in stressful situations; less stringent criteria may be acceptable in certain applications such as interiors.

However, it is necessary to be wary in using many of the standards quoted below. Firstly, some (especially the ASTM standards) were developed for massive masonry, and are not necessarily relevant to modern applications such as veneers. Secondly, the stresses on building stone vary markedly depending on the location and manner in which the stone is used. Therefore, stone which does not fully comply with the most stringent standards may in fact be adequate for certain low-stress applications. And finally, there still does not exist a complete and fully-accepted consensus as to which stone properties (and what values of those properties) are of relevance in deciding upon the suitability of stone for particular applications.

Further, stone is an extremely variable material. Although it would be desirable to find a stone which is excellent in respect of all criteria, such an ideal can rarely be attained. More commonly, a stone will have a mix of good and more mediocre qualities.

The upshot of all this is that it is necessary to weigh the importance of the various criteria in respect of the proposed stone application in order to decide whether the stone is adequate for the purpose. This requires experience of observing past stone performance, and an understanding of the nature of stone properties and behaviour, as much as reference to standard criteria.

Freshness

Sandstone must be quarried from below the natural surface zone of intense weathering, which may extend some metres below the original outcrop surface in badly weathered exposures. Stone in this zone can superficially appear fresh, and yet be considerably weaker than deeper, less altered stone.

Jointing breaks and fracturing

Joint breaks and fractures are unacceptable within a finished dimension stone piece, since they result in strength reduction and accelerated weathering.

They may be open (uncemented or only lightly cemented by iron oxides), or else cemented (annealed) by secondary mineral deposits. Fine, tight "hairline" fractures, if not strongly cemented, are just as unacceptable as major joint breaks.

Deep breaks should be spaced at least 2.0 metres apart (although stone with closer breaks may be usable for some purposes such as production of brick-size blocks or paving slabs). Blocks must be free of minor or incipient fractures.

Bedding

Blocks, veneers: Massive (or very faintly cross-bedded) stone in beds approx. 2.0 metres or more thick.

Tiles, slabs: Plane bedded or distinctly cross-bedded.

Colour

Stable (free of siderite, pyrite, marcasite).

Blocks, veneers: Uniform, patterning and imperfections absent or subdued.

Ornamental tiles, slabs, domestic "bricks": Strong patterning.

Texture

Fine to medium grained.

Moderately to well sorted.

Grains require moderate to high sphericity and minimal common orientation.

Intergranular texture

High percentage of quartz/quartz contacts (cut-off values are difficult to define; 20-30% may be adequate if other stone characteristics are good. 50% or above is an excellent value). Clay matrix should be predominantly in the form of interstitial fillings and pellets, rather than as intergranular layers and films.

Textural defects

Minimal or absent: quartz pebbles
 clay pellets
 clay or mud bands
 concretions
 porous spots

Chemical Composition

Chemical analysis of dimension stone is rarely of significance in regard to stone durability, except insofar as chemical composition is related to mineralogy.

Mineralogy

High percentage of quartz (minimum 60% (ASTM C 616); 85% or higher is ideal).

Low percentage of clay (10% or less is ideal, but 20% may be acceptable depending upon intergranular texture: small quantities of intergranular clay as layers and films can be more detrimental than larger amounts of interstitial clay and pellets).

Dense interstitial iron oxide cement may make a minor contribution to increasing stone strength, but its effect is generally overshadowed by clay and quartz proportions.

Deleterious minerals: Smectite: absent or trace only
 Mica: minimal, randomly distributed (concentration on bedding planes causes easy splitting).
 Graphite: as for mica.
 Feldspar and carbonate: minimal, less than 5% preferable.
 Gypsum, soluble salts; absent.

Unconfined Compressive Strength (UCS)

Oven-dried (65° C for 48 hrs):	35 MPa min.	(Spry 1983)
Soaked (in water for 48 hrs):	30 MPa min.	" "
Ratio wet/dry:	0.6 - 0.5 min.	" "

**Point Load Strength Index (Is50) .
(= tensile strength)**

Oven-dried (65° C for 48 hrs):	1.5 MPa min
Soaked (in water for 48 hrs):	1.25 MPa min.
Ratio wet/dry:	0.6 min

[-These values are calculated from the above compressive strength values using:

$$UCS = 24 \times (Is50) \quad (\text{Broch \& Franklin 1972})]$$

Flexural Strength & Modulus of Rupture

Related parameters, determined by different tests. Strength in bending. Important in design of thin veneers and paving tiles.

Flexural strength is of greater importance in veneers than modulus of rupture (Spry *in Gere et al.* 1989, p.51).

Medium strength:	2.1 - 7.0 MPa	(Spry 1988)
High strength:	7.1 - 15.0 MPa	" "

Effective Porosity (vol.%, 1 atm)

11.0% max; 8.0% ideal (Spry 1988)

Water Absorption (wt. %, 1 atm)

5.0% max. (Spry 1988)

Dry Bulk density (tonnes/cubic metre)

2.2 min. (Spry 1988)

[2.41 min. ASTM C 616]

Abrasion Resistance

Important criterion in paving applications (Spry 1988).

8.0 minimum Taber Abrasion Value (ASTM C 616)

Spry (1988, p.33) gives the following minimum values required for particular applications:

Use	Taber Abrasion Value (min)
light duty domestic	7
medium duty commercial	12
heavy duty	15

Dimensional Instability

Particularly important in design of thin veneers. Encompasses effects of thermal expansion (co-efficient of linear thermal expansion) and wet/dry swelling/contraction.

0.1% maximum linear dimensional change (Spry 1988, p.68).

Sodium Sulphate Soundness Test (full immersion) - (Spry 1983, 1988):

% mass loss at 15 cycles	Durability Classification
< 1	A
1 - 5	B
6 - 10	C
>10	D

Ultrasonic Pulse Velocity (Spry 1983):

>3000 metres/second:

High strength stone

2000 - 3000 m/s:

May be good quality stone, depending on other characteristics.

<2000 m/s:

Likely to be low quality stone.

Elasticity (Young's Modulus)

Important in the design of thin veneers. Limiting values not available to this author at the time of writing.

A 4.3 STONE TESTING METHODS

Most of the test methods for determination of the criteria listed in Section A 4.2 are discussed in detail in Appendix 3.

Many of the tests required for building stone evaluation have been standardised by the American Society for Testing and Materials (ASTM), and the standard test methods may be found in the annual ASTM Standards book (Vol. 04.08: Soil & Rock, Building Stones).

In addition, the Standards Association of Australia (SAA) set up a working group in 1982 to prepare a set of Australian building stone testing standards (Working Group CE/12/6/4 - Methods for Sampling and Testing Building Stones). Draft standards for a number of tests have been completed, as noted below.

Compressive Strength

ASTM C 170: Standard Test Method for Compressive Strength of Natural Building Stone.

SAA (draft): Compressive Strength.

Point Load Strength Index

See: Broch & Franklin (1972)

Bieniawski & Franklin (1972)

Modulus of Rupture

ASTM C 99: Standard Test Method for Modulus of Rupture of Natural Building Stone.

SAA (draft): Modulus of Rupture.

Flexural Strength

ASTM C 880: Flexural Strength.

SAA (draft): Flexural Strength of Stone Products.

Water Absorption, Effective Porosity, Bulk Density

ASTM C 97: Standard Test Method for Absorption and Bulk Specific Gravity of Natural Building Stone.

SAA (draft): Water Absorption, Apparent Porosity and Bulk Density of Building Stone.

Abrasion Resistance

ASTM C 241: Standard Test Method for Abrasion Resistance of Stone subjected to Foot Traffic.

ASTM C 18: Abrasion Resistance.

SAA (In Prep.): Abrasion Resistance.

Dimensional Instability

A relatively new test method, not yet fully standardised. The test is being developed at the AMDEL laboratory (South Australia).

SAA (In Prep.): Dimensional Instability.

Sodium Sulphate Soundness Test

SAA (draft): Sodium Sulphate Soundness Test (Full Immersion)

APPENDIX FIVE

DATA RECORDING SHEETS

This appendix consists of data recording sheets developed during this project. Full details of the various data collection procedures are given in Appendix Three.

The data collection sheets are listed below, with brief explanatory comments on each:

(1) SANDSTONE HAND SPECIMEN / THIN SECTION DATA SHEET

See Appendix Three, sections (A 3.1.1), (A 3.2), (A 3.3.1), (A 3.3.2).

Quartz cement - Usually in the form of authigenic overgrowths, but counted as "monocrystalline quartz" since it is often difficult to differentiate from clastic quartz grains.

Iron oxides - Ferruginous cement, mainly iron hydroxide. Clay which is simply stained brown by iron oxides is counted as "clay matrix" ; only dense iron oxide masses (which have completely replaced or displaced clay masses) are counted as "iron oxide cement".

Intergranular texture - See Data Sheet (2) for line traverse data sheet used in compiling this information.

(2) INTERGRANULAR TEXTURE - LINE TRAVERSE DATA SHEET

See Appendix Three, section (A 3.2.3).

This data sheet is used to compile the information recorded under "Intergranular Texture" on the sandstone hand specimen / thin section data sheet. For each contact counted, a mark is placed in the appropriate column. After sufficient contacts have been counted, the marks are tallied, calculations performed, and information transferred to the thin section data sheet.

(3) X - RAY DIFFRACTION - QUANTITATIVE CLAY COMPOSITION DATA SHEET

See Appendix Three, section (A 3.1.2 (B)).

This data sheet is used to calculate relative volumetric proportions of clay minerals identified in a single specimen by X - Ray diffraction.

The principal (usually 001) peak for each clay mineral is identified and its area measured (eg, by measuring peak height above background, and peak width at background level (usually in mm). Peak area is then $(\text{height} \times \text{width}) / 2$).

Peak areas are then adjusted according to the multiplication factors given in Table (A 3.2) in Appendix Three, and the resulting adjusted peak areas are summed to give a total peak area.

One percent of total clay volume is then equal to this total peak area divided by 100. Volumetric percentages of each clay mineral can then be calculated by dividing adjusted peak areas for each clay mineral by the calculated figure for 1% of totalled peak areas.

(4) POROSITY DATA SHEET

Includes Effective Porosity, Water Absorption and Bulk Density.

See Appendix Three, section (A 3.4.1).

(5) POINT LOAD STRENGTH INDEX DATA SHEET

See Appendix Three, section (A 3.4.2)

(6) SODIUM SULPHATE FULL IMMERSION TEST - DATA SHEET

See Appendix Three, section (A 3.5.1).

(7) ULTRASONIC PULSE VELOCITY (PUNDIT) - DATA SHEET

See Appendix Three, section (A 3.4.3)

SANDSTONE HAND SPECIMEN / THIN SECTION DATA SHEET

SPECIMEN No.:
SOURCE LOCALITY / SITE:
GEOLOGICAL AGE / FORMATION:
SEDIMENTOLOGICAL CLASSIFICATION:

COLOUR:

DRY

WET

Fresh surface

Weathered surface

DIAGENETIC/WEATHERING COLOURATION/EFFECTS

HOMOGENEITY/STRUCTURES:

COHERENCE:

GRAINSIZE:

SORTING:

OTHER FEATURES:

THIN SECTION

CLASTS.

Mean

Max.

Min

Grainsize class

Grainsize. Diameter (mm)

Sorting class.

σ Standard Deviation.

Grainshape: Roundness:

Sphericity.

Grain orientation:

COMPOSITION: No. of points counted: _____			
	Mineral	%	Types / comments
Clasts	Monocrystalline Quartz		
	Polycrystalline Rock fragments		
	Feldspar		
	Mica		
Matrix	Clay		
Cement	Iron oxide (dense masses)		

INTERGRANULAR TEXTURE: No. of contacts counted: _____

CONTACT CATEGORIES

%

Clay Contact Types (% of category)

Interstitial clay and pellets

Intergranular clay layers and films

Contact categories: Quartz / Quartz

Quartz / Clay

Quartz / dense Iron oxide

Clay / dense Iron oxide

TOTAL

OTHER FEATURES.

THIN SECTION PETROGRAPHY - INTERGRANULAR TEXTURE

LINE TRAVERSE DATA SHEET

No. of contacts counted: _____

CONTACT TYPES						
Quartz / Quartz	Quartz / Clay		Quartz / Dense Iron Oxide Cement	Clay / Dense Iron Oxide Cement		
	(Q/C)			(C/Fe)		
(Q / Q)	Interstitial clay masses or pellets	Intergranular clay films or layers	(Q / Fe)	Interstitial clay masses or pellets	Intergranular clay films or layers	
						TOTAL
Total Count						
TOTAL						
%s						
%s of clay contact categories						

X-RAY DIFFRACTION: QUANTITATIVE CLAY COMPOSITION DATA SHEET

Clay Mineral	Area under principal Peak (normally 001)	Peak area adjusted by weighting factor	Percentage of total clay matrix

Total Adjusted Peak Areas: _____

1% of total peak areas
(= 1% of total clay volume): _____

Specimen: _____

Total Adjusted Peak Areas: _____

1% of total peak areas
(= 1% of total clay volume): _____

Specimen: _____

Total Adjusted Peak Areas: _____

1% of total peak areas
(= 1% of total clay volume): _____

POROSITY DATA SHEET

(includes Effective Porosity, Water Absorption & Bulk Density)

Specimen: _____ Source: _____

Specimen pre-treatment:

Air Temperature during tests: 20° C

Time water absorption commenced:

Time water absorption completed:

Sample No.		1	2	3	
DATA:	Dry Weight (Wd)				gms
	Saturated Weight (Ws)				gms (48 hours)
	Bulk Volume (Vs)				mls (= (10mm) ³)

CALCULATIONS:

Average				
	Dry Bulk Rock Density (Dd)			tonnes/metre ³
	Effective Porosity (Peff)			volume %
	Water Absorption (Wabs)			weight %

BULK VOLUME (Vs): Volume of water displaced by saturated sample. (millilitres)
 = volume of specimen including pores.

DRY BULK ROCK DENSITY: $Dd = Wd/Vs$ (tonnes/metre³) (= Density of dry specimen including pores)

EFFECTIVE POROSITY: $Peff = ((Ws - Wd)/Vs) \times 100$ (vol.%)
 = (pore volume/bulk volume), since pore volume = (Ws - Wd)/dt
 where dt = specific gravity of water = 1 at 20° C

WATER ABSORPTION: $Wabs = ((Ws - Wd)/Wd) \times 100$ (wt.%)

POINT LOAD STRENGTH INDEX - DATA SHEET

Specimen No. _____

Test No.	Orientation	Moisture Content	Load at Failure (kN) P	Platen separation (mm) D	Is(50) = $140 \cdot P \cdot (D^{-1.5})$ MPa (Fitzhardinge 1978)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

NOTES: Orientation: + = tensile stress normal to bedding
 // = tensile stress parallel to bedding
 X = orientation with respect to bedding uncertain

Moisture content: D = oven-dried (65° C for 48 hrs)
 N = air-dried (natural water content at 20° C)
 S = saturated in water for 48 hrs.

CALCULATIONS:

Av. Is(50) // bedding (MPa)

Av. Is(50) + bedding (MPa)

Av. Is(50) X (MPa)

Anisotropy Index:

$$I_a(50) = (Av.Is(50)//) / (Av.Is(50) +)$$

oven-dried (D)	air-dried (N)	saturated (S)

Wet/dry strength ratios:

Is(50) // bedding

Is(50) + bedding

Is(50) X

Av. of ratios ((// + +)/2)

saturated/oven-dried (S/D)	saturated/air-dried (S/N)

SODIUM SULPHATE FULL IMMERSION TEST - DATA SHEET

SPECIMEN No.:

SOURCE:

DATES - Start:

Finish:

NATURE OF SPECIMEN:

DEPARTURES FROM STANDARD:

OPERATOR:

LABORATORY:

Sample No.

Size/Shape

Imperfections/structures

		Dry Weight (grams) after each cycle (incl. twine/tag/salt)		Condition
Prior to first soak, dry	(m1)			
After cycle No.	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
	11			
	12			
	13			
	14			
	15			
After final wash/dry	(m2)			
After 3 day soak/dry	(m3)			

Average			
% mass loss after cycle 15 :			
$C15 = ((m1 - m2)/m1) \times 100$			
% mass loss after 3 day soak :			
$D = ((m1 - m3)/m1) \times 100$			

ULTRASONIC PULSE VELOCITY (PUNDIT) - DATA SHEET

DATE:

SPECIMEN No.:

NATURE OF SPECIMEN:

TESTING LOCATION:

GENERAL CONDITION OF STONE / TEST SURFACES:

FRACTURES, INHOMOGENEITIES, COMMENTS:

[illegible]

SPECIMENS COLLECTED FOR TESTING (7) :

DIAGRAM OF SPECIMEN (where relevant) SHOWING TEST POINTS AND LOCATIONS OF SPECIMENS COLLECTED:

NOTES:

- (1) Test point numbers, as per diagram.
- (2) Orientation of direct line between transmitter and receiver, with respect to bedding. (// = parallel to bed, + = normal to bed, \ = diagonal to bed, X = unknown)
- (3) Weathered, fresh and rough, fresh and ground flat, etc.
- (4) Direct, Semi-direct, Indirect.
- (5) Separation of transducer heads (test points) in a straight line.
- (6) Transit time in seconds (T) = (transit time in μ - seconds) / 1,000,000
- (7) Specimen no.s, location of each specimen w.r.t. test points, as shown in diagram.

APPENDIX SIX**ULTRASONIC PULSE VELOCITY MEASUREMENT FOR RAPID FIELD
ASSESSMENT OF BUILDING SANDSTONE QUALITY**

This appendix is a copy of Sharples (1985a), and is referred to in Chapter Six of this thesis.

National Estate Tasmania

Grant No. 10 1984/85

ULTRASONIC PULSE VELOCITY MEASUREMENT FOR RAPID
FIELD ASSESSMENT OF BUILDING SANDSTONE QUALITY

WITH

COMMENTS ON OTHER POTENTIAL RAPID-TESTING
METHODS FOR BUILDING SANDSTONES

by

C.E. Sharples
Department of Mines
Tasmania

October 1985

Department of Mines, Tasmania

(1)

ACKNOWLEDGEMENTS

This work was made possible by a grant from the National Estate, Tasmania, and has been supervised and assisted by M.R. Banks (University of Tasmania), P. Spratt (England, Newton, Spratt and Murphy Pty Ltd), and I. Jennings (Department of Mines).

Thanks are due to:

The Hydro-Electric Commission of Tasmania: Loan of PUNDIT instrument

John Dunn, Stonemason, Launceston: For access to rough and sawn
stone blocks in his yard

Leonie Jones, University of Tasmania: Useful discussions

(11)

CONTENTS

	Page No.
Acknowledgements	i
Contents	11
Figures	1v
ABSTRACT	v
 SECTION ONE : INTRODUCTION	 1
(1.1) Origin and aim of the present project	1
(1.2) Project administration	1
(1.3) General methodology	2
 SECTION TWO : IN SITU SANDSTONE TESTING METHODS	 3
(2.1) The aims of in situ testing	3
(2.2) Potential in situ sandstone testing methods	4
(2.2.1) Clay content determination-staining techniques	4
(2.2.2) Assessment of other sandstone properties	4
(2.2.2.1) Ultrasonic pulse velocity measurement	5
(2.2.2.2) Surface hardness testing - The Schmidt Hammer	5
(2.2.2.3) Seismic methods	6
(2.2.2.4) Gamma/gamma density probes	6
(2.2.2.5) Neutron probes	7
(2.2.2.6) Radar	8
(2.2.2.7) Infra-red thermography	8
(2.2.2.8) Resistivity	8
(2.2.2.9) Other methods	9
(2.3) Ultrasonic Pulse Velocity measurement - the in situ testing method chosen for assessment	9
 SECTION THREE : THE THEORY OF ULTRASONIC PULSE VELOCITY MEASUREMENT	 10
(3.1) Equipment	10
(3.2) Fundamental Principles of Ultrasonic Pulse Velocity measurement in sandstone	10
(3.2.1) Elastic waves in solids	10
(3.2.2) Measurement of Ultrasonic Pulse Velocity in elastic solids	11

(iii)

SECTION FOUR : CORRELATION OF ULTRASONIC PULSE VELOCITY	13
WITH SANDSTONE PROPERTIES	
(4.1) Preamble	13
(4.2) Procedure	13
(4.3) Summary of laboratory UPV measurements and statistical analysis	16
(4.4) Discussion of laboratory UPV measurements	16
(A) Correlation of UPV with individual sandstone properties	17
(B) Correlation of UPV with combined sandstone properties	18
(C) Correlation of UPV with durability in the salt test	19
(D) UPV anisotropy	19
(4.5) Conclusions	19
SECTION FIVE : ULTRASONIC PULSE VELOCITY MEASUREMENT IN THE FIELD	22
(5.1) Introduction	22
(5.2) Field UPV measurement procedures	22
(5.3) Field UPV tests conducted	24
(5.3.1) Test samples	24
(5.3.2) Direct UPV measurements, smooth-sawn and rough blocks	24
(5.3.3) Semi-direct UPV measurements, smooth-sawn and rough blocks	25
(5.3.4) Indirect UPV measurements, smooth-sawn and rough blocks	27
SECTION SIX : CONCLUSIONS - USEFULNESS OF UPV MEASUREMENT	30
AND RECOMMENDED PROCEDURES	
(6.1) Summary of conclusions	30
(6.2) The value of UPV measurement	32
(6.3) Recommended procedures	33
SECTION SEVEN : REFERENCES	35
APPENDIX ONE : LABORATORY ULTRASONIC PULSE VELOCITY MEASUREMENTS	
- Data obtained	
APPENDIX TWO : FIELD ULTRASONIC PULSE VELOCITY MEASUREMENTS	
- Field data sheets	

FIGURES

Fig. No.		After Page No.
(4.1)	Transit time vs Path length : all lab. results	16
(4.2)	UPV vs Point Load Strength Index (S)	17
(4.3)	UPV vs Porosity (P)	17
(4.4)	UPV vs Detrimental Clay content (C)	17
(4.5)	UPV vs Total Clay content (TC)	17
(4.6)	UPV vs S/P	18
(4.7)	UPV vs S/P + C	18
(4.8)	UPV vs S/P + TC	18
(4.9)	UPV vs Salt test results	18
(5.1)	PUNDIT transducers in three possible modes	22
(5.2)	Transit time vs Path length : All field results	24
(5.3)	Transit time vs Path length : Direct mode measurements	24
(5.4)	Transit time vs Path length : Semi-direct mode measurements	25
(5.5)	UPV vs Path length : Semi-direct mode measurements	25
(5.6)	Transit time vs Path length : Indirect mode measurements	27
(5.7)	UPV vs Path length : Indirect mode measurements	27
	- smooth blocks	
(5.8)	UPV vs Path length : Indirect mode measurements	27
	- rough blocks	

Note:-

The originals of Figs. (4.2)-(4.9) incl. are housed at the Department of Mines, Tasmania (Drawing Nos. 5128 (a-h)).

ABSTRACT

Ultrasonic Pulse Velocity (UPV) measurement was investigated as the most promising technique presently available for rapidly assessing the quality (durability) of building sandstones.

Laboratory testing established that UPV measurements have a slightly better than fifty per cent correlation with strength and porosity, which are two of the most important parameters of building sandstone quality. However, UPV measurement gives no direct indication of swelling clay content.

UPV is not so much a tool for precisely determining the particular properties of a sandstone, but rather is a property in its own right, which can broadly be thought of as a resultant of a number of other sandstone properties of relevance to durability.

Field testing showed that UPV testing is best suited to rapid testing of large smooth-sawn sandstone blocks. It is less-well suited, but still feasible, for rough blocks and certain types of quarry faces, but is almost useless for testing broad and flat (but not smooth) quarry faces.

The value of UPV measurement is that it will quite sensitively and rapidly distinguish between the better and worse blocks in a related suite of sandstone blocks. However, for a reliable quality-control procedure, it is also necessary to select a small number of representative samples for laboratory testing (particularly X-ray diffraction for clay content), so as to provide reference data for the suite of blocks, or the stone source, as a whole.

Section ONE

INTRODUCTION

1.1 Origin and Aim of the present project

In 1983/1984 the National Estate funded a research project (Grant No. 3 1982/83) on Tasmanian building sandstones, (Sharples et al., 1984) which identified the major properties which determine sandstone quality and resistance or otherwise to decay in buildings. Laboratory techniques of assessing these properties were developed, and an inventory was compiled of the properties of both present and past major Tasmanian building sandstones.

It was found that stone quality varies markedly within some quarries as well as between quarries. The methods of testing employed for the 1984 report, being largely based on laboratory testing methods, gave accurate data but were very time consuming and did not allow rapid detailed testing of either potential new stone sources or of the stone quality variation within a quarry.

The aim of the present project was to continue this work by determining and evaluating potential methods of quick in situ testing of sandstone, so as to enable detailed testing of proposed stone sources prior to quarrying, and to allow quality control testing of individual stone blocks as they are prepared by the stonemason. These methods should also allow the rapid assessment of the quality of stone already in place in buildings.

1.2 Project Administration

The present project was financed by the National Estate under Grant No. 10 1984/85. The work has again been done by Chris Sharples, under the supervision of Mr Ian Jennings (Department of Mines), Dr Max Banks (Geology Department, University of Tasmania) and Mr Peter Spratt (England, Newton, Spratt and Murphy Pty Ltd). The facilities of both the University and the Department of Mines were again made available to the project in the form of working space, laboratory facilities, transport and field equipment.

2.

1.1 General Methodology

A wide range of potential rapid in situ testing methods were considered (see Section Two). Of all these, it appeared that Ultrasonic Pulse Velocity measurement was by far the most promising method, and it was decided to concentrate on it.

The method was initially tested in the laboratory, using prepared samples of a wide range of sandstones which had been tested in detail by the laboratory techniques used in Sharples et al (1984). Some field testing was undertaken, followed by laboratory testing of field samples using the old time-consuming but reliable methods. In this way it was possible to very reliably determine the degree to which Ultrasonic Pulse Velocity (UPV) measurements on a stone correlate with such durability-related properties as tensile strength, porosity and clay content. (see Section Four and Appendix One for the results of this part of the investigation).

Having thus determined in a quantitative way the degree to which UPV measurements can be used to determine the durability-related properties of a sandstone, further field tests were done. Large sandstone blocks were selected in order to determine the procedures and limitations inherent in using the UPV method in differing situations, such as flat quarry faces, rough quarried blocks, and sawn and worked blocks. It was found that there are important variations in UPV readings in these various situations. (see Section Five and Appendix Two).

Section TWO

IN SITU SANDSTONE TESTING METHODS

2.1 The aims of in situ testing

In Sharples et al (1984) it was proposed that the most important sandstone properties from the point of view of durability were tensile strength (measured in the form of the 'Point Load Strength Index'), effective porosity, and clay content (especially the presence of the clay smectite). These are properties which have hitherto been determined in the laboratory. The primary purpose of assessing techniques of in situ testing is therefore to determine to what extent, and how, it may be possible to rapidly determine stone quality.

There are a number of other important factors in choosing good stone for building purposes. These factors include the degree of weathering, colour, fracturing, the presence of inhomogeneities such as clay bands. Such factors have traditionally been visually determined in the quarry, and will continue to be so determined.

Most in situ rock tests developed to date are designed to test the properties of large masses of rock, for purposes such as testing foundations for large engineering works (e.g. see Jumakis 1979). Thus, for instance, in situ porosity tests take account not only of intergranular porosity (which is relevant to building stone assessment), but also fracture porosity (which would not be relevant to building stone assessment, as rock masses free of fracturing would be used).

The need to determine in situ the properties of relatively small masses of rock is a departure from traditional methods and purposes of in situ rock testing.

The requirements for an in situ sandstone quality testing method are that the method be rapid, and capable of being applied in circumstances such as a flat quarry face, a rough outcrop, or on sawn blocks of varying sizes. In order to be of use in quality control testing of sawn blocks, an in situ test must be non-destructive.

4.

2.2 Potential in situ sandstone testing methods

2.2.1 Clay content determination-Staining techniques

The presence of the swelling clay smectite (also known as montmorillonite) is one of the three major factors in durability of Tasmanian sandstone, and it is usually determined in the laboratory by X-ray diffraction analysis (Sharples *et al.* 1984).

The only presently known potential in situ method of determining smectite presence or absence in sandstone is a clay-staining technique described in Allan and Lawrence (1972 p. 109) and Grim (1968). The method revolves around applying benzidine to clay mixtures (including sandstones with a clay matrix). If smectite is present, a blue-purple staining will result; otherwise there is no colour change.

Although it is unlikely that such a method could give a quantitative assessment of smectite content, simple determination in situ of the presence or absence of smectite would be of critical value in stone quality-assessment in situ.

Unfortunately, the clay-staining technique is inappropriate for in situ use due to safety reasons: Benzidine is an extremely potent carcinogen, requiring full body protection and respirators for safe handling (Sittig 1981). The extraordinary precautions needed to use benzidine safely in the field are such as to actually make laboratory XRD testing for smectite less complicated and time-consuming than in situ testing with benzidine.

For this reason, the clay-staining technique was abandoned as a useful in situ test and laboratory X-ray diffraction remains at present the most efficient means for determining smectite content in potential building stone.

2.2.2 Assessment of other sandstone properties

The remaining potential in situ testing methods examined below are all methods intended to provide a measure of properties other than smectite content, in particular tensile strength and/or effective porosity, which are the other important factors in Tasmanian sandstone durability apart from smectite content.

2.2.2.1 Ultrasonic Pulse Velocity Measurement

In effect, this is a 'mini-seismic' test of the rock. The test involves measuring the velocity of ultrasonic sound waves ('longitudinal' or compressive P body waves, in seismological terminology) travelling through the sandstone.

The Ultrasonic Pulse Velocity (UPV) is known to be governed by a large number of factors, including factors related to durability such as strength and porosity. Sengupta (1975 p. 66) gives the optimistic assessment that 'In fact, sonic velocity could be a cumulative indication of all the parameters which influence the durability of the rock'.

In fact, as shown later in this report, it appears that stone strength is the single most important factor in sandstone UPV, with porosity also playing a significant role. In addition, UPV measurements can sometimes isolate specific inhomogeneities in sandstone, such as fractures, hard or soft patches, and weathered areas.

Due to the potential usefulness of the UPV method, together with its ease of use and non-destructiveness, Ultrasonic Pulse Velocity measurement was chosen as the in situ test method most worthy of assessment. The bulk of this report is devoted to an assessment of the UPV method.

2.2.2.2 Surface hardness testing - the Schmidt Hammer

The Schmidt hammer (Winkler 1973, p. 36) is a convenient method of measuring the surface hardness of rocks ('Schmidt Hardness'), a property which is held by Winkler to be semi-logarithmically related to compressive strength. If the stone surface is unweathered, a compressive strength obtained with the Schmidt hammer ought to be representative of the compressive strength of the whole body of rock tested. Since compressive strength and tensile strength are related (see for instance Bell 1983 (a), p. 511-515), the Schmidt hammer can give a useful non-destructive in situ assessment of sandstone strength.

The Schmidt hammer has a number of drawbacks, however. In the first place it does not actually measure the strength of the body of a rock mass; strictly it only measures the surface hardness, and body strengths are inferred from this. Such inferences are only valid if: a) the rock mass is homogenous, a characteristic which must be determined by some other means; and b) if the surface layer is in fact completely fresh and unweathered. It is very common indeed,

6.

in natural outcrops, old quarry faces, and even in dimension blocks in a building, for the surface layers of a sandstone to be case-hardened so that they have an unrepresentatively high surface hardness.

The Schmidt hammer is also affected by the roughness of the surfaces tested (Williams & Robinson 1983), so that surfaces need careful preparation for testing.

For these reasons the Schmidt hammer was not tested in detail.

2.2.2.3 Seismic methods

Seismic methods are essentially identical to Ultrasonic Pulse Velocity methods, the only difference being that seismic methods are used to study much larger rock masses than are studied by the UPV methods described in this report.

Since such large scale determination of rock properties has little relevance to building stone studies, in which we want to detect variations in stone properties over distances of less than a metre, seismic methods are not seriously considered as a method of in situ sandstone durability assessment.

2.2.2.4 Gamma/gamma density probes

Gamma/gamma probes essentially measure the density of electrons (i.e. number of electrons per unit volume) in a rock, which correlates directly to the bulk density, and thus the porosity of the rock (although it is affected by the density of the fluids or gases occupying the pore spaces).

The gamma/gamma probe has a gamma ray source of known intensity which bombards the rock with gamma rays. Backscattering of the gamma rays occurs at a rate proportional to the electron density (i.e. actual bulk density) of the rock, and this backscattered radiation is measured by a detector situated a fixed distance from the radioactive source. The measured radiation together with the known fixed parameters allows the density of the rock to be calculated.

Two types of density probe are of possible use in sandstone studies. The most common is a down-hole probe used in borehole logging. This would only have limited use in sandstone studies, on occasions when boreholes are available in quarries.

The other type of density probe is a surface density probe which can be applied to flat surfaces, and is sometimes used in road engineering studies. Such a probe could probably be used on quarry faces for effective porosity determination, and is worthy of further consideration and testing.

The surface density probe was not tested in the present project, since the gamma ray source associated with the probe is an energetic radioactive source which must be shielded and used with great care. It was considered that, at this stage, the problems associated with the safe use of the density probe made it a less attractive method for detailed assessment than the ultrasonic pulse velocity method.

2.2.2.5. Neutron probes

Neutron probes have been developed to measure the abundance of hydrogen atoms in rocks encountered by boreholes. Thus in a water-saturated sandstone, the neutron log should indicate the combined effect of the porosity (filled with water, H_2O) and the clay content (most clays are hydrous as opposed to quartz and feldspar, which contain no significant H). However, the probe would not differentiate particular clay types.

Neutron probes emit neutrons from a radioactive source. When these neutrons are captured by the nucleus of a hydrogen atom, high-energy gamma radiation is emitted which is detected by the probe.

Neutron probes have a number of problems from the point of view of sandstone testing. First of all, most available neutron probes are designed for use in boreholes rather than on quarry surfaces and the like. Secondly, any surface neutron probe would face similar problems to gamma probes insofar as shielding the radioactive source goes.

A problem in analysing data from a neutron probe used on superficial outcrops is that one would need to independently measure the degree of water-saturation of the rock in order to be able to differentiate the effect of pore water from that of clay content on the log obtained.

Because of these problems, the neutron probe was not investigated further in this project.

8.

2.2.2.6 Radar

Radar is sometimes used for detecting discontinuities such as faults and fractures in rock and concrete. It could thus be used for evaluating the degree of fracturing in a quarry site.

Radar equipment and the interpretation of results is still experimental, and whilst promising there is at present neither the equipment nor the data available for use.

2.2.2.7 Infra-red thermography

Infra-red thermography detects minute differences in temperature on the surface of rocks or other materials. Such temperature differences can result from varying percentages of void spaces (i.e. porosity) beneath the surface, and could potentially result from the varying thermal properties of particular minerals present in varying proportions.

The simplest method of performing infra-red thermography is by the use of infra-red photography. This method has previously been tested by Peter Spratt ([pers.comm.](#)) on sandstone buildings. He found that surface discolouration caused temperature variations completely masking any effects due to the underlying stone.

It therefore appears that, should infra-red thermography in fact yield information of relevance to in situ sandstone quality testing, it would only do so in exceptional cases where surfaces were not marked by weathering, iron staining, or other alterations.

Infra-red thermography is therefore not regarded as a promising tool for in situ testing of sandstone quality.

2.2.2.8 Resistivity

Resistivity is a commonly used geophysical technique whereby the resistivity of a body of rock is measured by passing an electric current through it. Resistivity is affected by numerous factors, including pore water content (equals porosity for saturated rocks), mineralogy including clay content, groundwater salinity, degree of saturation, permeability, transmissivity, and other factors.

Although some of the factors determining rock resistivity are of importance to sandstone durability, it would in practice be difficult to isolate the effects on resistivity of those factors relevant to durability.

For this reason, resistivity was not investigated further as a potential testing method.

2.2.2.9 Other methods

Other established geophysical methods such as electrical, magnetic, gravimetric or radiometric methods appear to have little usefulness for sandstone durability studies.

The possibility remains of developing entirely new in situ tests specifically for sandstone durability. For instance, an instrument designed to assess the presence of Mg in typical Tasmanian quartz arenite sandstones would be useful in differentiating smectite clays (together with any chlorite or vermiculite), from the other clay and non-clay minerals normally found in those sandstones.

Such developmental work was not undertaken in this project; the emphasis of this project was rather to assess existing testing methods from the standpoint of sandstone durability.

2.3 Ultrasonic Pulse Velocity Measurement - the in situ method chosen for assessment

As a consequence of the considerations detailed in section 2.2 this project concentrated on assessing the usefulness of Ultrasonic Pulse Velocity (UPV) measurement as a tool for in situ determination of sandstone quality for building purposes.

The remainder of this report consists of a detailed assessment of the UPV method, and a concluding section recommending an overall strategy for assessing sandstone for building purposes, both in the quarry and in worked blocks.

10.

Section THREE

THE THEORY OF ULTRASONIC PULSE VELOCITY MEASUREMENT

3.1 Equipment

In this project, Ultrasonic Pulse Velocity (UPV) was measured using an instrument known as the PUNDIT (Portable Ultrasonic Non-destructive Digital Indicating Tester), manufactured by C.N.S. Instruments Ltd of 61-63 Holmes Road, London, NW5, U.K. Although designed for UPV measurement of concrete, the instrument proves eminently suitable for use on sandstone. Being lightweight and battery-powered, the instrument is convenient for field use. Operating details are contained in the operator's manual, and special details of importance to field sandstone testing are discussed in Section Five of this report.

During this project a PUNDIT kindly loaned by the Hydro-Electric Commission of Tasmania was used; at the time of writing the Tasmanian Department of Mines is acquiring its own PUNDIT.

3.2 Fundamental principles of ultrasonic pulse velocity measurement in sandstone

3.2.1 Elastic waves in solids

Sonic waves travelling in a small solid such as a block of sandstone are the same phenomenon as seismic waves which are more commonly studied in large rock masses, such as the Earth as a whole (Stacey 1969).

Seismic waves are classified in two main classes, Body waves (those which travel through the body of the rock) and Surface waves (those which travel primarily along the surface of a rock mass). The main types are:

Body waves P waves - 'longitudinal' or compressional

S waves - 'rotational' or shear

Surface waves Rayleigh waves - ellipsoidal particle movements

Love waves - a wave type caused by multiple reflections of body waves between the surface and an internal discontinuity (which in the Earth is the Mohorovičić Discontinuity).

11.

As a broad rule, in a given solid, P waves travel about 1.7 times faster than S waves, Rayleigh waves travel about 0.9 times as fast as S waves, and in the Earth, Love waves travel at about the same speed as S waves under the Moho (Tucker et al. 1970). Clark (1966) and Carmichael (1982) give data on laboratory measurements of sonic (seismic) wave velocities in a large number of rock types, including basalt, limestone and sandstone. Their data indicates that P wave velocities are always faster than S wave velocities in these materials, often by a factor of two. Clark (1966) also notes that field (large scale) and lab. (small scale) seismic velocities are identical for identical rock types.

It is thus clear that P waves are the fastest seismic (sonic) waves in an elastic solid, and therefore that any device, such as the PUNDIT, which is designed to measure the velocity of first-arrival waves, will be measuring P-wave velocities.

The velocity of P-waves in a solid depends on the density and elastic properties of the solid. Since important sandstone properties such as porosity and intergranular bonding (strength) are major determinants of density and elastic properties, it is theoretically to be expected that P-wave velocities in sandstone will correlate with strength and porosity, as well as with factors such as total clay matrix content which also affect strength.

Sonic velocities are independent of the frequency of the sonic waves, as long as the least lateral dimension of the solid (i.e. the dimension perpendicular to the direction of wave travel) is not less than the wavelength of the sonic waves (PUNDIT manual). Transducers generating 50 kHz and 82 kHz sonic pulses are supplied with the PUNDIT. Thus, when using 50 kHz transducers a least lateral dimension of 80 mm is required, and less when using 82 kHz transducers. (Note however that experimental results from the present project showed that specimens several centimetres smaller than the 80 mm limit can be tested with minimal distortion of results compared to larger specimens of the same material).

3.2.2 Measurement of ultrasonic pulse velocity in elastic solids

The PUNDIT equipment includes two transducers which are applied to the surface of the specimen with a suitable agent such as vaseline, in order to give good acoustic coupling. One transducer generates ultrasonic pulses (at either 50 kHz or 82 kHz), which travel through the specimen. The first arrival (P) waves are detected by the other

12.

transducer, and the PUNDIT measures the transit time (T) for the P-wave travelling between the two transducers. The distance between the transducers (path length, L) is measured by the operator, and the Ultrasonic Pulse Velocity (UPV) of the specimen can then be calculated, as:

$$\text{UPV} = \frac{L}{T} \quad (\text{metres per second})$$

The transmitting transducer propagates P-waves mainly in a direction normal to the transducer face - thus, directly through the specimen away from the surface on which the transducer rests. However, a small proportion (1-2%) of the P-wave energy travels along the surface of the specimen on which the transmitting transducer rests, due to scattering of P-waves by the many discontinuities (grain boundaries, etc.) with the sandstone.

This means that, until the sonic energy is dissipated (e.g. into the air), first arrival waves measured on the same surface of a specimen as that to which the transmitter is applied will be surficially-propagated P-waves rather than the slower 'true' surface waves mentioned in Section 3.2.1 above.

Section Four

CORRELATION OF ULTRASONIC PULSE VELOCITY WITH SANDSTONE PROPERTIES

4.1 Preamble

As outlined in Section 1.3, the first step in assessing the value of UPV measurement for sandstones quality assessment was to perform detailed laboratory testing of the method to quantitatively determine the relationship between UPV and the properties of tested sandstones. This section describes only the procedure and important conclusions from that investigation. The detailed data results are contained in Appendix One.

4.2 Procedure

In the course of previous sandstone studies (Sharples et al 1984) a large number of sandstone samples had been sawn into regular blocks averaging 40 x 70 x 70 mm. Since the properties of these specimens had previously been determined by laboratory methods they provided excellent specimens on which to conduct initial UPV measurements for comparison with a range of sandstone properties. (Although the blocks are a little smaller than the minimum dimensions recommended in the PUNDIT manual - see Section 3.2.1 - the results obtained were consistent with one another and with results later obtained from larger blocks. This indicates that any distortion of UPV readings was negligible.).

Accordingly, 93 of these individual sawn blocks, comprising sandstone from 49 specimens from 30 different quarries or other sources, were tested for Ultrasonic Pulse Velocity, using the 'direct method' whereby the transmitting and receiving transducers are placed directly opposite each other on either side of the block. (It was known beforehand, and the results of this project have confirmed, that this direct method gives consistent and accurate UPV measurements for sandstone). Each block was tested in several orientations, so that in those cases where bedding direction was apparent, the UPV parallel and perpendicular to bedding could be compared.

The various UPV values obtained from each of the 49 specimens were averaged, yielding 49 UPV values as a basic data bank. The most important sandstone properties from the point of view of stone durability (See Section 2.1 and Sharples et al. 1984), being the tensile strength (more precisely, Point Load Strength Index) (S), effective

14.

porosity (P), total clay content (TC) and detrimental (smectite) clay content (C), had already been measured for all these specimens (Sharples et al. 1984). It was therefore possible to statistically compare each of these properties with the UPV of the specimens, so as to determine whether, and to what degree, these properties determine a sandstone's UPV.

The four properties were compared both individually and in combinations (see below) with UPV. In addition, UPV was compared to data previously obtained from the cyclic salt test (Sharples et al. 1984, Section 8.5.3). In the cyclic salt test sandstone specimens are subjected to repeated cycles of saturation in NaCl solution with alternate heating and freezing of saturated specimens. Rates of specimen breakdown (which can be quite rapid), are measured and used as another criterion of sandstone durability. In this work, sandstone durability in the salt test is defined as volume percentage loss after ten cycles.

All these parameters were initially compared to (plotted graphically against) UPV in both a linear and a logarithmic fashion; it was found that in all cases the logarithmic comparison gave a stronger correlation to UPV than the linear comparison.

Regression analysis was performed on each comparison, and a correlation co-efficient r calculated, from which is obtained the useful figure $100r^2$, which tells us the degree (as a percentage) to which variation in one of the parameters considered accounts for variation in the other parameter. Thus, if we (hypothetically) derived a 100^2r value of 100% for the relationship of strength to UPV, then we would be able to say that UPV of a rock is completely determined by the strength of the rock. More realistically, if we obtain a 100^2r value of 50% for the relationship of UPV to a particular parameter, then we can suppose that the UPV of the rock is 50% determined by that parameter, and 50% determined by some other parameter or group of parameters.

In this way, it was possible to determine the degree to which the sandstone properties of strength (S), porosity (P), total clay content (TC) and detrimental clay (smectite) content (C) are individually related to sandstone UPV. The logic behind then comparing UPV to combinations of these parameters is as follows:

15.

It became apparent (see below) from the regression analysis that no single one of these properties accounts for any more than just under half of the variation in UPV, so that it can be supposed that UPV is rather the net resultant of these (and perhaps other) properties. By mathematically combining properties we can attempt to improve our quantitative knowledge of which sandstone properties have the greatest influence on UPV.

It is clear (Sharples et al. 1984 Section B:3.3) that as strength (S) increases, so sandstone durability increases. Conversely, as porosity (P), total clay content (TC) and detrimental clay content (C) increase, so durability decreases. Thus, at the simplest level, in attempting to assess the combined effect of these properties on durability, we must use a function in which durability is directly proportional to strength, and inversely proportional to porosity, total clay and detrimental clay content.

Since our purpose in assessing the factors determining UPV is ultimately to see whether UPV is related to durability, it is therefore most useful to compare UPV to combinations of sandstone properties mathematically combined in ways which ought to correspond to sandstone durability. With this in mind, the following simple combinations were tested:

S/P Strength and porosity combined in a fashion reflecting the effect each has on durability.

2S/P As above, with double value given to strength due to the fact (see below) that strength (by itself) appears to have twice as much influence on UPV as porosity does by itself.

$\frac{S}{P + TC}$ Strength, porosity and total clay content combined in a fashion reflecting the effect each has on durability.

$\frac{S}{P + C}$ Strength, porosity and detrimental clay content combined in a fashion reflecting the effect each has on durability.

These are very simple relationships, and it is probable that further study could reveal mathematical combinations of these parameters which would more faithfully represent the physical processes relating these sandstone properties to durability and to UPV, thus allowing a fuller accounting for the parameters involved in determining sandstone UPV.

4.3 Summary of laboratory UPV measurements and statistical analysis

The following table and figures summarise the data (each data point represents the average value for each specimen), and statistical analysis thereof, obtained from measuring the UPV of small sawn blocks in the laboratory. A listing of the data can be found in Appendix 1.

TABLE 4.1 Correlation of various parameters with Ultrasonic Pulse Velocity (UPV)

Parameter correlated with UPV	Regression Analysis	
	Linear correlation ($100r^2$)	Logarithmic correlation ($100r^2$)
Point Load Strength Index, Mpa (S)	40.59%	47.997%
Effective Porosity, Vol. % (P)	21.10%	23.26%
Total Clay, Vol. % (TC)	*	*
Detrimental Clay, Vol. % (C)	*	*
S/P	38.43%	50.84%
2S/P (No diagram)	-	50.38%
$\frac{S}{P + TC}$	-	47.59%
$\frac{S}{P + C}$	-	47.12%
Durability in Salt Test, Vol. % loss	*	*

* Diagrams indicate any correlation is quite low, therefore not calculated

4.4 Discussion of laboratory UPV measurements

Figure 4.1 indicates that the measurements obtained conform well to a straight-line path-length/transit-time relationship. The scatter which is present can reasonably be assumed to result from actual UPV variations between the various specimens concerned (since different UPVs should give straight lines of different slope on a path-length/transit-time diagram).

We can thus say, both for the abovementioned reasons and also on the grounds of what would be theoretically expected, that the UPVs obtained by direct measurement of sawn sandstone blocks of small size can be considered to be the 'actual' UPVs of the specimens concerned.

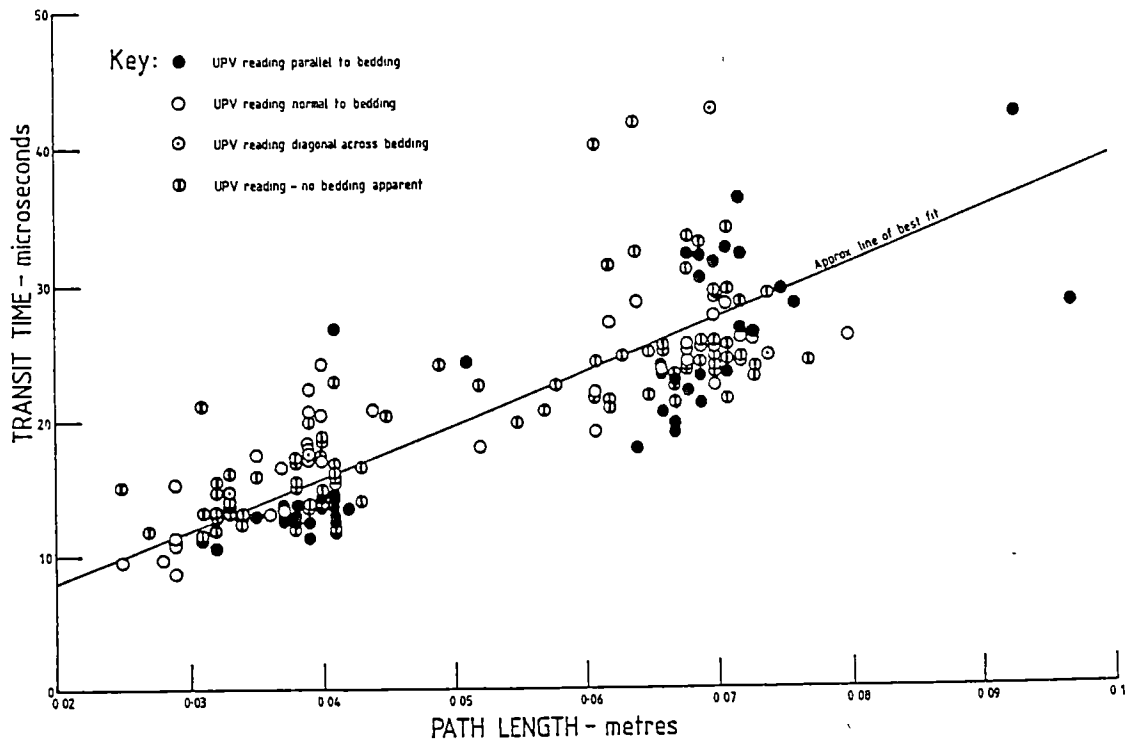


Figure (4.1) Transit time vs Path Length: Direct mode Ultrasonic Pulse Velocity (UPV) measurements on all laboratory specimens.

Line of best fit is from visual estimation only. All data is contained in Appendix One. Scatter around the line is due largely to actual variations in UPV of the various specimens.

17.

The laboratory and statistical results allow the following conclusions to be drawn:

(A) Correlation of UPV with individual sandstone properties

The most important single sandstone property controlling variation in UPV is tensile strength (i.e. Point Load Strength Index), with 48% control. UPV increases as strength increases.

The next most important property (of those tested) is effective porosity (23% control). UPV decreases as porosity increases.

The clay content of the sandstone, taken either as total clay or as swelling (detrimental) clay content only, appear from the data to have little direct effect on UPV. Nonetheless, it can be suspected that clay content would have some indirect effects on UPV, mainly because clay content is itself a major factor contributing to strength and porosity.

The problem in isolating the effects of clay on sandstone UPV stems also from the distribution of clay in a sandstone. For instance, whereas clay coating grains around an open pore would have little effect on stone strength or porosity, clay filling interstices between grains and binding those grains would contribute significantly to both strength and porosity. Thus, it is not the total clay content, but the microscopic distribution of the total clay which is important. A statistical method of treating clay content in this fashion to enable correlation with UPV has not been developed in this project, and so the effect of clay content on UPV cannot presently be considered other than as a contributing influence on strength and porosity.

These results quantitatively support, for Tasmanian sandstones, the opinion of Fertl (in Yen & Chilingarian 1976 p. 202) that ultrasonic velocity in rocks is related to lithology type (i.e. strength, clay content, etc.), porosity, and types of fluids in the pore space.

The fact that strength, by itself, correlates more closely with UPV than does porosity by itself is due to the fact that it is the intergranular bonds - which determine strength - which are the major carriers of the ultrasonic sound energy. More bonding (= greater strength) results in better facilitation of sound propagation, and a higher proportion of silica than clay bonds (also = greater strength), will also facilitate faster propagation of sound (Carmichael 1982 indicates mineral quartz has a P-wave velocity of about 6.05 km/sec,

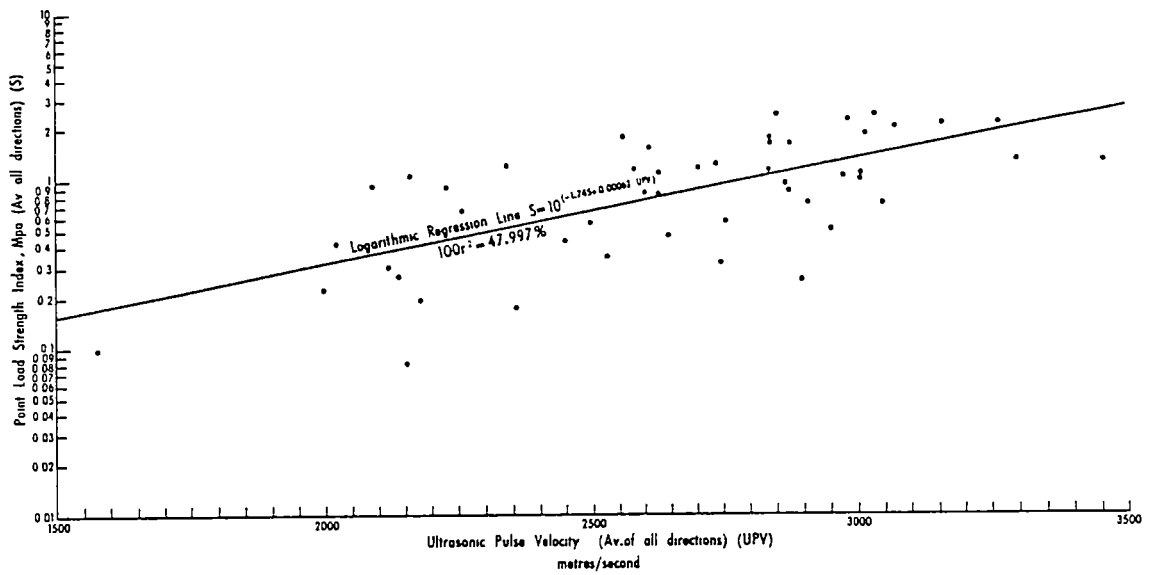


Figure (4.2) Ultrasonic Pulse Velocity vs Point Load Strength Index (S)
Laboratory results.

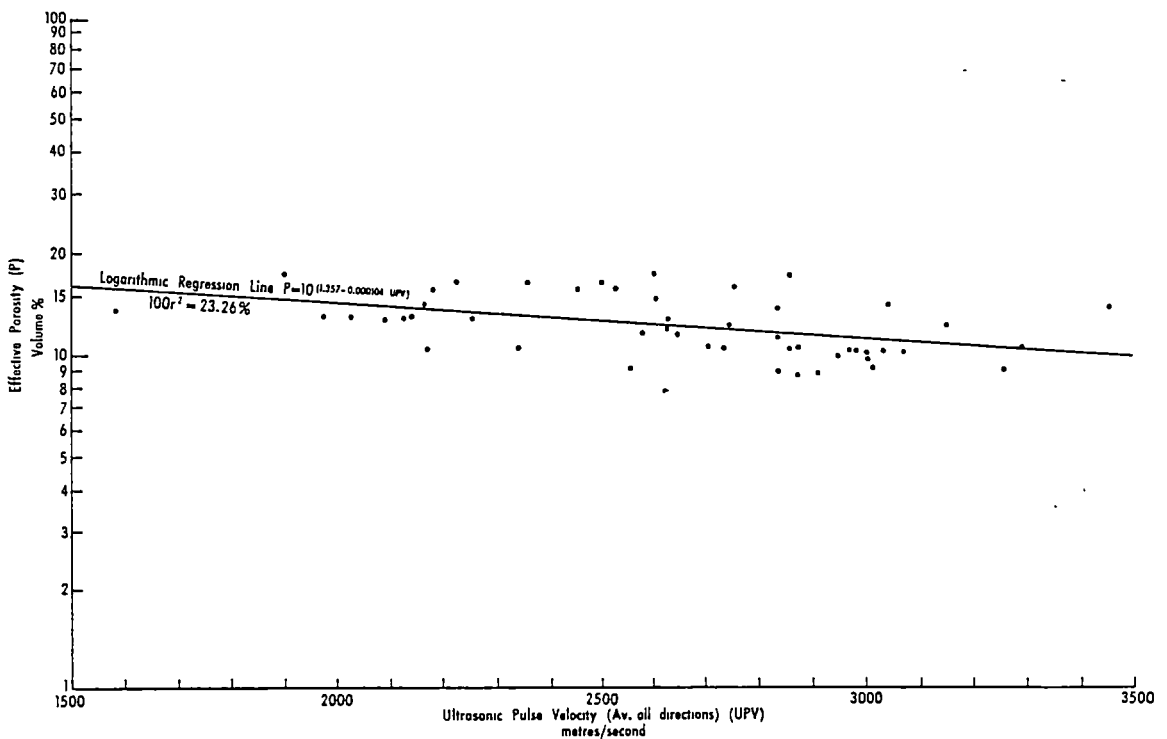


Figure (4.3) Ultrasonic Pulse Velocity vs Porosity (P)
Laboratory Results.

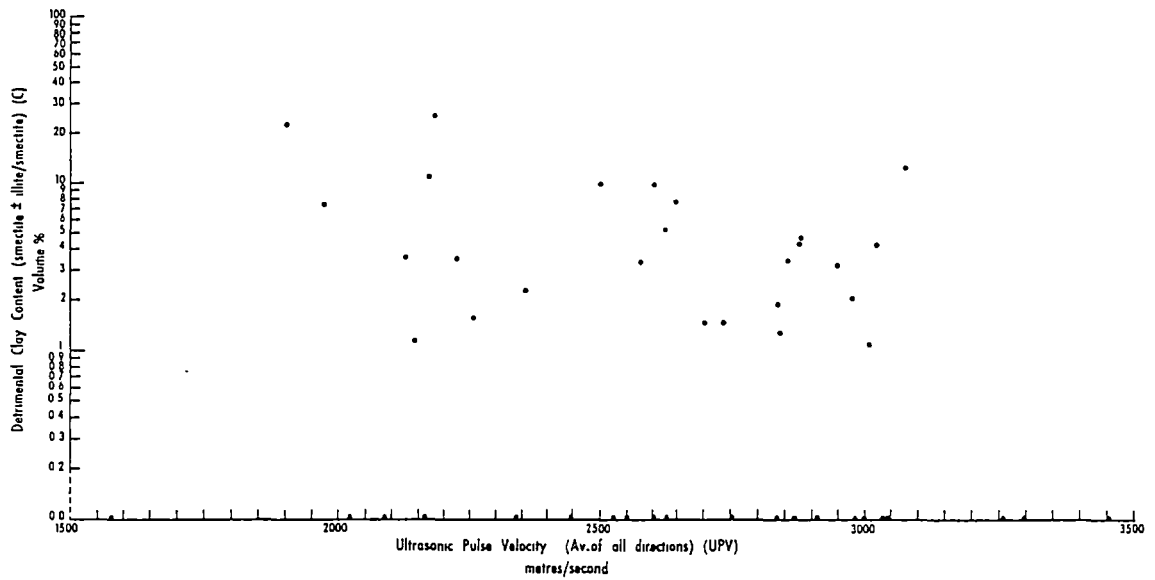


Figure (4.4) Ultrasonic Pulse Velocity vs Detrimental Clay Content (C)

Laboratory results. 'Detrimental clay' refers to the swelling clay Smectite, but not Vermiculite

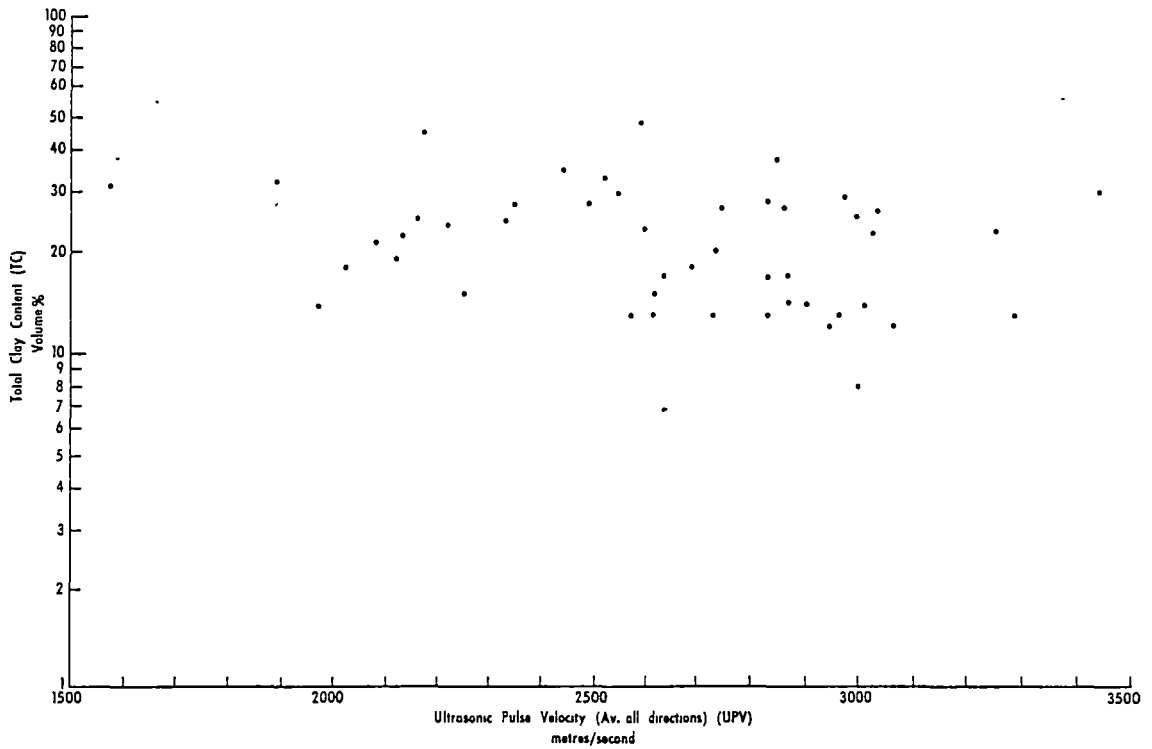


Figure (4.5) Ultrasonic Pulse Velocity vs Total Clay Content (TC)

Laboratory results. Total clay includes all clay types present.

18.

as compared to clays which (in aggregate masses) have P-wave velocities in the range 1.4 - 1.6 km/sec).

In contrast, while increasing porosity has the effect of slowing sound transmission (because soundwaves travel faster in the mineral matter than they do in the air or other fluids filling pores) there is generally sufficient intergranular bonding to carry the sound so that only a dramatic increase in porosity will suffice to cause a significant lowering of UPV in the specimen as a whole.

(B) Correlation of UPV with combined sandstone properties

The best correlation with UPV is obtained by combining strength and porosity in the form S/P. UPV increases as S/P increases. However, the correlation obtained, nearly 51%, is only 3% better than the correlation with S alone. Attempting to enhance this correlation by weighting S and P according to their individual correlations with UPV (i.e. 2S/P) has no effect other than to slightly decrease the correlation with UPV.

The correlation of UPV with the combination S/P does not result in an arithmetically increased correlation - that is the individual correlations with strength (48%) and porosity (23%) do not add to give a correlation of 71%, nor does any other simple arithmetic manipulation yield the actual combined correlation of 51%. This appears to be the result of the fact that the fundamental causes of both strength and porosity are often identical or 'overlapping' (e.g. clay content, degree of compaction). Therefore, since many of the same fundamental factors are involved in both strength and porosity, combining S and P does not combine two wholly different sets of parameters, but rather two sets of overlapping parameters which already have many factors in common. Thus, the combined correlation of the two overlapping sets of parameters is only a little greater than the correlation of the most important set - those contributing to strength - alone.

Attempting to include the clay content as a parameter correlating with UPV (i.e. S/P + TC & S/P + C) is of no use - in fact it decreases the correlation to approximately 47%. As discussed above, this is probably because clay content is already a factor contributing to strength and porosity, so that considering it as a separate factor in its own right, and trying to combine it in that sense with S and P, only tends to confuse the situation and thus lower the degree of correlation.

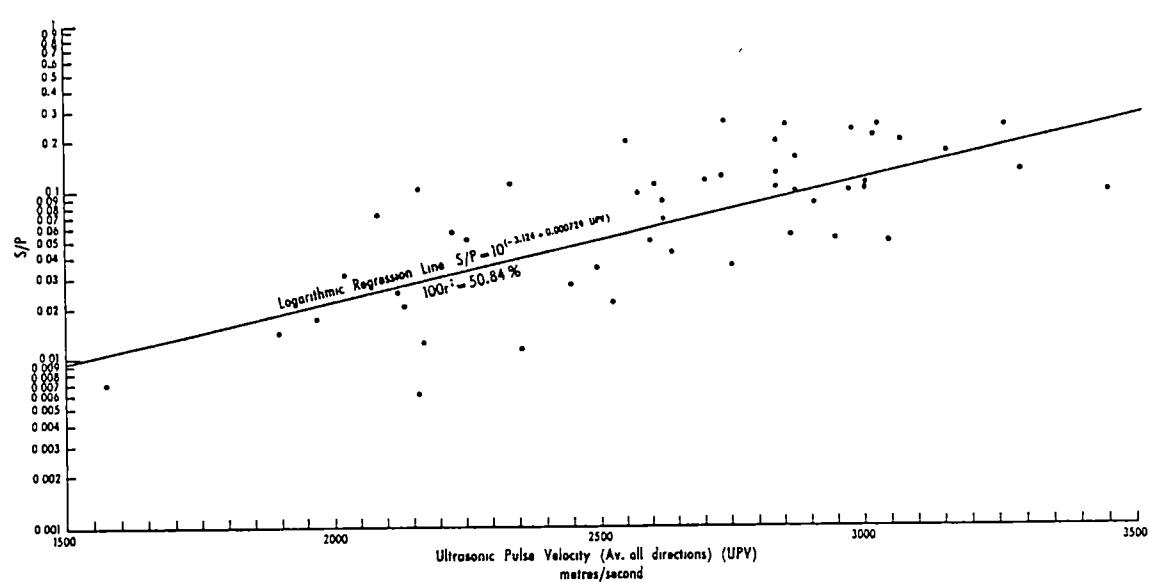


Figure (4.6) Ultrasonic Pulse Velocity vs Strength/Porosity (S/P)
Laboratory results.

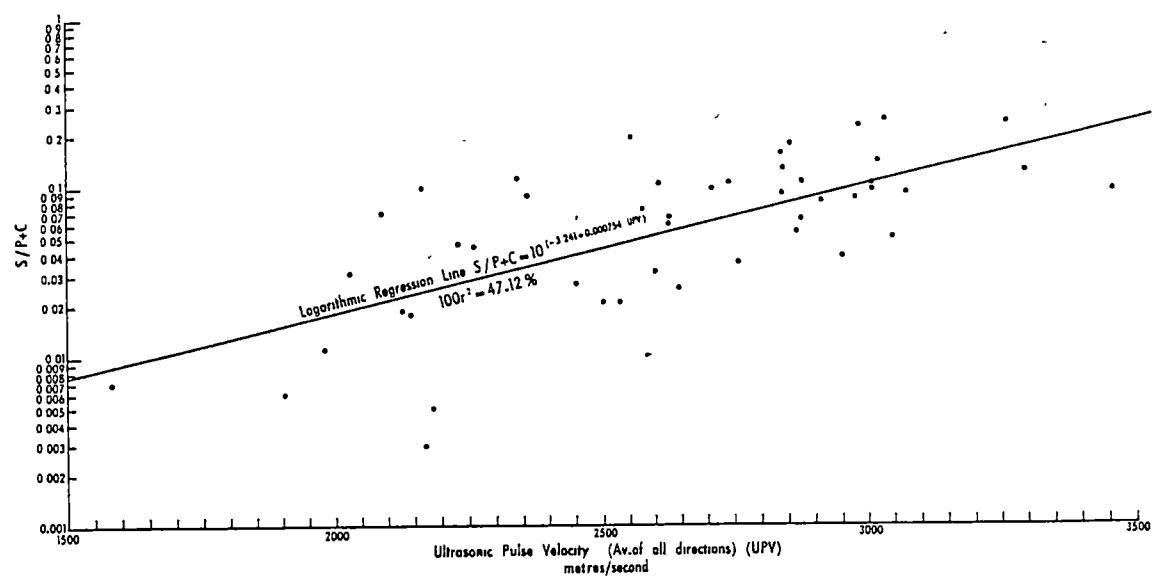


Figure (4.7) Ultrasonic Pulse Velocity vs Strength/Porosity + Detrimental Clay Content (S/P+C)
Laboratory results.

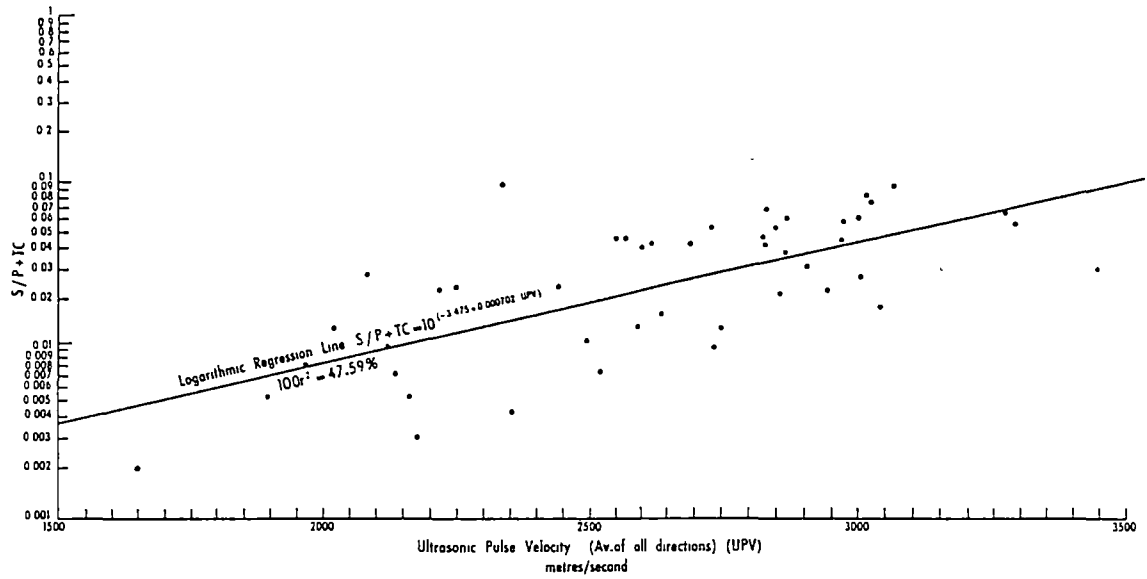


Figure (4.8) Ultrasonic Pulse Velocity vs Strength/Porosity + Total Clay Content ($S/P+TC$)

Laboratory results.

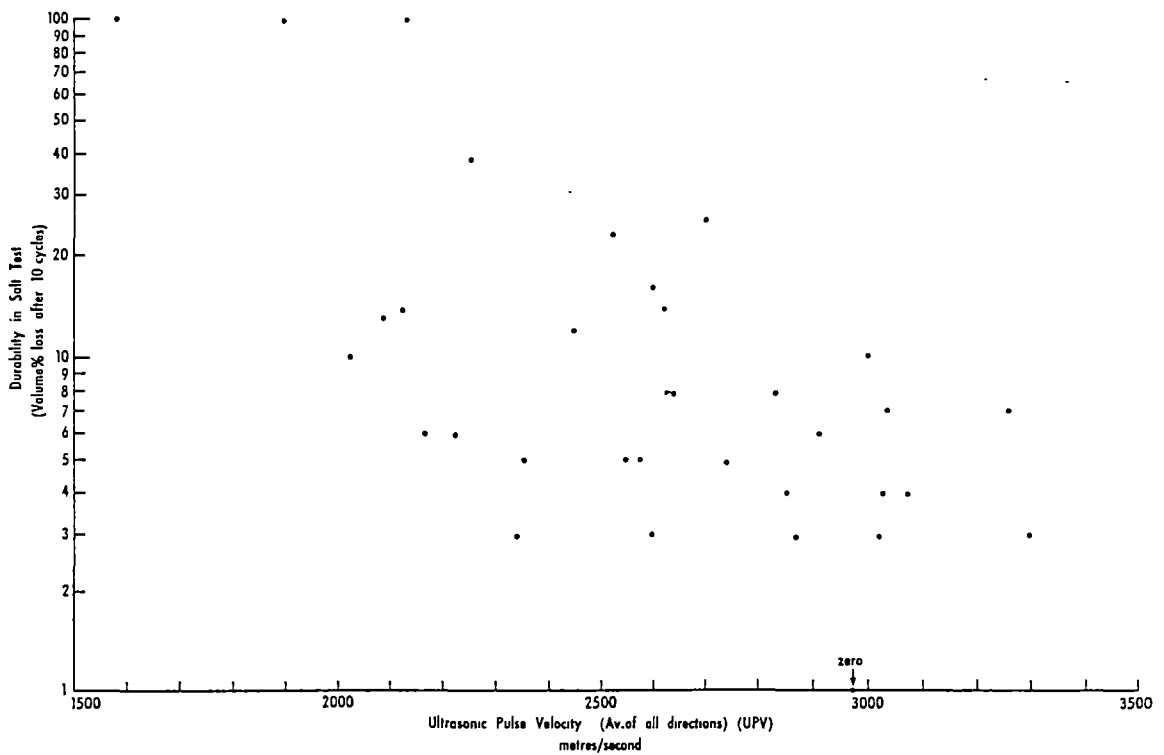


Figure (4.9) Ultrasonic Pulse Velocity vs Cyclic Salt Test Results

Based on Laboratory UPV tests and previous salt tests detailed in Sharples et al 1984.

(C) Correlation of UPV with durability in the salt test

A very broad correlation exists between Ultrasonic Pulse Velocity and durability in the salt test (Fig. 4.9) but not sufficiently good to be worth performing a regression analysis.

Broadly, UPV increases as Salt Test Durability increases. This result is to be expected, since both these parameters are considered to relate to sandstone durability. However, since both parameters are the net resultant of a large number of individual factors, it is not surprising that there is not a tight correlation between the two.

(D) UPV anisotropy

Specimens with well defined bedding tend to show a marked UPV anisotropy, with higher ultrasonic pulse velocities parallel to bedding planes and lower velocities across (perpendicular to) bedding planes.

(Note that although the general trend is to higher UPV with higher stone strengths, within individual specimens the UPV is often highest in the direction of lowest strength, i.e. parallel to bedding. This is due to the better sound transmission along the bedding planes, in which particles are often aligned and along which there may be discontinuities or layers which impede sound transmission perpendicular to those layers).

Specimens which are massive or have poorly defined bedding tend to show little or no UPV anisotropy.

4.5 Conclusions

We can account for just over 50% of variation of ultrasonic pulse velocity in sandstones in terms of tensile strength (Point Load Strength Index) and effective porosity, combined in the form S/P. As the function S/P increases (implying greater stone durability) so too does UPV increase, from a low of around 2000 metres/second for poor stone, to a high of 3000 to 3500 m/sec for good stone.

The strength taken by itself is the single most important stone parameter governing UPV in sandstone.

Since just over 50% of variation in UPV in sandstone is controlled by two factors - strength and porosity - which are most important in durability, it is clear that the UPV method is a useful indicator of stone durability. Although 50% correlation is far from perfect,

it is certainly significant, and indicates that we have identified the major factors in sandstone UPV.

It is probable that the other (just under) 50% of UPV variation is controlled by a host of minor factors which would be difficult to fully account for in a practical situation. Such factors may include:

- Moisture content: may cause small UPV variations
but would have been a constant in the present work since all specimens tested had been held at 20°C for over one year in the same room, and would thus have similar moisture contents.
- Clay content: effects not encompassed by strength and porosity.
- Fractures or discontinuities in the stone.
- Variations due to stone UPV anisotropy not properly averaged out.
- Minor experimental and measuring inaccuracies.
- Minor distortion of results in small blocks.

In a suite of samples taken from a single quarry it is likely that many minor factors would be a constant for the quarry, allowing UPV variations to be more closely related to strength and porosity.

An indication of the usefulness of UPV measurements on Tasmanian sandstones is that the method actually gives a 6% better correlation with strength and porosity than does the more widely used cyclic salt test (see Sharples et al. 1984). In dealing with a material as complex as sandstone we probably could not hope for a correlation of better than the approximate 50% correlation we do in fact get between UPV and the major durability-related factors of strength and porosity.

In conclusion, ultrasonic pulse velocity is not a perfect tool, but it can give a useful indication of variation of strength and porosity in sandstone. In cases where it is desired to determine which were the most durable of a suite of related samples (e.g. blocks in or from a single quarry), the measurement of UPV would be a sufficient method, provided X-ray diffractograms were prepared for a number of samples in order to also assess swelling clay content.

21.

The measurement of UPV could furthermore provide quantitative values for strength & porosity if a small number of a related suite of tested samples were subjected to full laboratory testing as reference samples.

Section FIVE

ULTRASONIC PULSE VELOCITY MEASUREMENT IN THE FIELD

5.1 Introduction

In the laboratory tests described in the previous section, UPV measurements were made under ideal conditions, by measuring directly from one side to the other of a smooth-sawn block.

In practical situations it may sometimes be possible to conduct UPV tests under similar ideal conditions - as, for instance, when doing quality control tests on sawn blocks in the stonemason's workshop. However, under many circumstances, such as testing stone in situ in a quarry, or in rough unsawn blocks, such ideal conditions do not occur. It may not be possible to measure directly through a rock mass; one may have to measure 'semi-directly' (around a corner) or 'indirectly' (along a single surface). As well, one may have to content with rough surfaces with which it is harder to achieve good acoustic coupling for the transducer heads.

It has therefore been necessary to investigate the behaviour of UPV in these non-ideal situations, in order to discover any variations and special conditions which may have to be taken into account when using UPV measurement in practical field situations.

This section (and Appendix Two) detail the investigations made into the practical field application of UPV measurement.

5.2 Field UPV measurement procedures

There are essentially three ways of arranging PUNDIT transducer heads on a mass of stone for UPV measurement. These are the Direct, Semi-direct and Indirect arrangements, as illustrated in Figure (5.1).

The direct transmission method is the ideal because the P-wave ultrasonic pulses are mainly propagated in the direction normal to the transducer face, i.e., directly through the specimen away from the transmitting transducer head.

Semi-direct measurement works quite well since a significant amount of P-wave energy is scattered at angles less than 90° to the transducer face, so that semi-direct measurement essentially involves direct transmission of ultrasonic pulses through the rock, but at lower intensities.

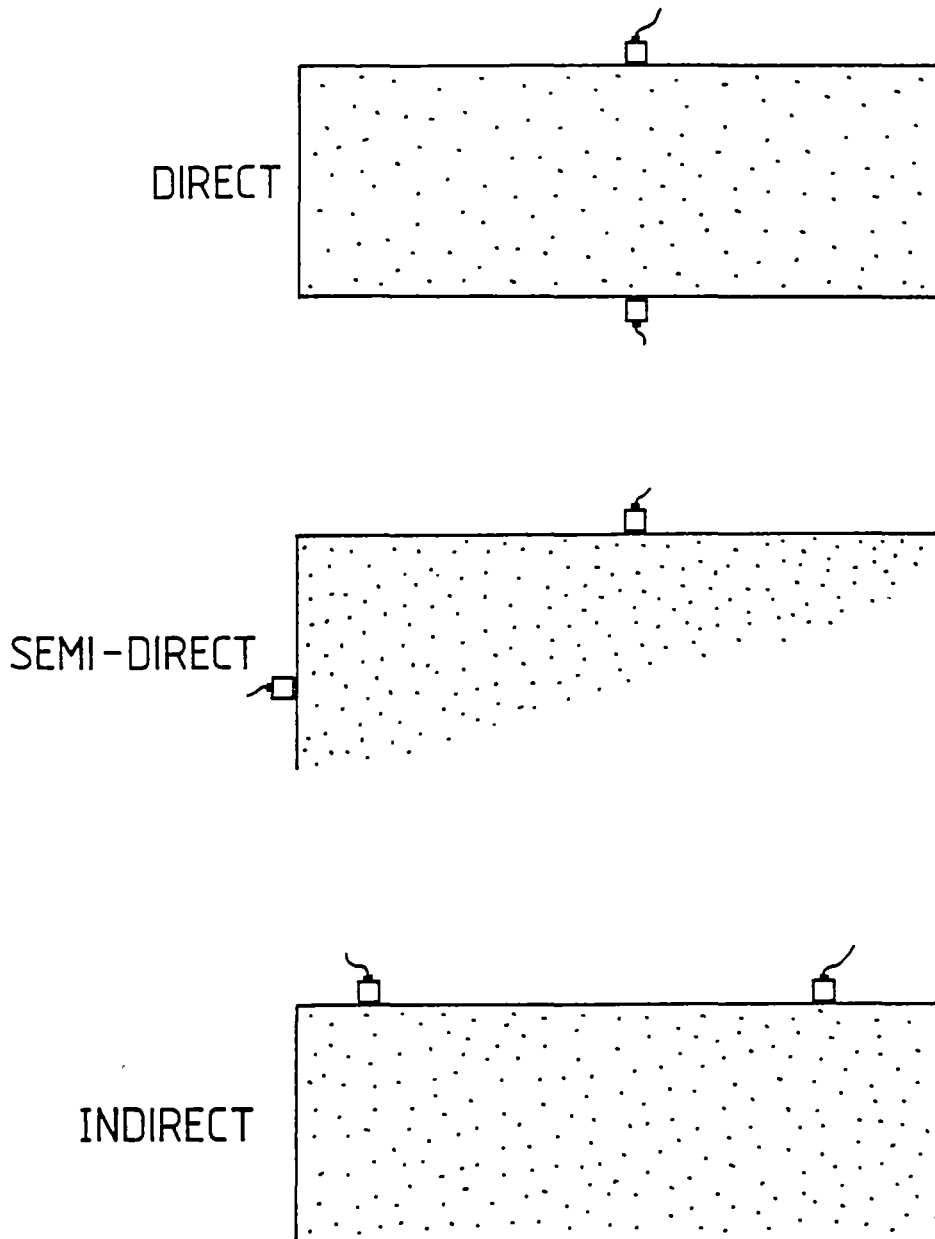


Figure (5.1) PUNDIT transducers in three possible modes for propagation of ultrasonic pulses in sandstone.

23.

The Indirect method is possible because the P-wave energy is scattered by the many discontinuities (grain boundaries, etc.) within the sandstone so that some P-wave energy (about 1% or 2% of the energy transmitted directly, according to PUNDIT manual) travels directly along the surface on which the transmitting transducer rests. As indicated later, however, indirect UPV measurement appears to be complicated by the transmission of true surface waves (Rayleigh Waves).

Obviously there are situations, such as flat quarry faces, where the less satisfactory Indirect measuring technique would be the only UPV technique possible; it is therefore important to investigate the usefulness of the indirect technique.

The basic procedure for taking UPV measurements has already been outlined in Section Three of this report, and is discussed in detail in the PUNDIT manual.

Next to the arrangement of transducer heads, the most important aspect of setting the equipment up for UPV measurements is the acoustic coupling of the transducer heads with the sandstone surface. It is of utmost importance that there be good contact, with no gaps, between transducer head and sandstone. Any gaps, however thin, act as a fracture in the rock, and significantly reduce the measured ('apparent') velocity of the Ultrasonic Pulse.

A sawn block surface is generally quite flat, and will generally give excellent acoustic coupling with only the application of a small amount of vaseline or similar couplant to the transducer face. A good indication that satisfactory coupling has been achieved is that the transit time displayed by the PUNDIT readout will remain constant to within 1% or so, even when transducers are removed and re-applied.

It is impossible to get good coupling with a rough rock surface. In such cases an area large enough to accommodate the transducer head must be ground flat, either by hand with a carborundum block, or by a mechanical grinder. If the surface so provided is quite flat, coupling can then be achieved, as above, with the use of a little vaseline.

24.

Very often, however, surfaces ground 'flat' in this manner are not completely flat, and may therefore give anomalous results. The procedure in such cases is to cover the measuring spot with plaster of Paris, cement mortar or epoxy resin, set the transducer head in this, and allow the couplant material to set.

5.3 Field UPV tests conducted

5.3.1 Test samples

Thanks to the generous co-operation of John Dunn (Launceston Stonemason), investigations were carried out on large rough and sawn blocks of Nunamara and Linden sandstone (See Sharples et al. 1984). In addition, a few results were obtained from the Teatree Quarry. These three stone types have closely similar strengths and porosities, and thus form a homogeneous group of test samples for UPV measurement. The following average figures are from Sharples et al. (1984):

	Point Load Strength Index (MPa)	Effective Porosity (Vol. %)
Nunamara	1.19	10.66
Linden	1.47	10.47
Teatree	1.13	10.35

The three methods (direct, semi-direct, indirect) were all tested on both smooth sawn blocks and on rough blocks with testing spots ground flat with a hand-operated grinder. In both cases vaseline was used as a couplant, without plaster, mortar or epoxy resin.

Figure (5.2) records all the results obtained in graphic form, and the original data is recorded in Appendix Two. The following subsections discuss and interpret the results obtained.

5.3.2 Direct UPV measurement, smooth-sawn and rough blocks

Figure (5.3) illustrates the results obtained by direct testing of smooth sawn and rough blocks. In most cases, several measurements were done on the same blocks at differing path lengths.

Direct UPV measurements made on smooth sawn blocks give very consistent and reliable results up to path lengths (see Section 3.2.2) of about 1.2 metres. The fact that all such measurements fall into a narrow straight envelope on Figure (5.3) means that closely similar UPV results are obtained on the same specimens at varying path lengths.

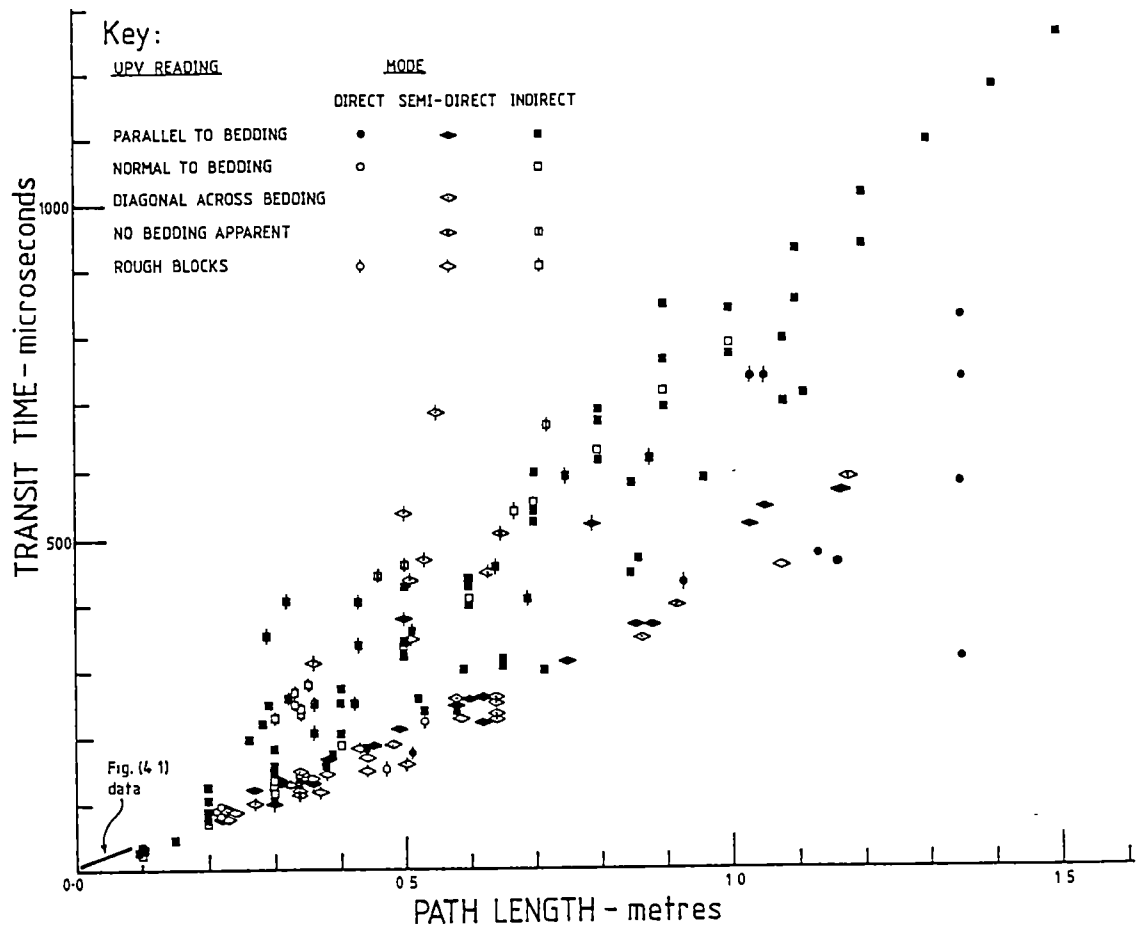


Figure (5.2) Transit Time vs Path Length: All modes, all field results

(Rough and smooth sawn blocks of Teatree, Nunamara and Linden sandstone). All data contained in Appendix Two.

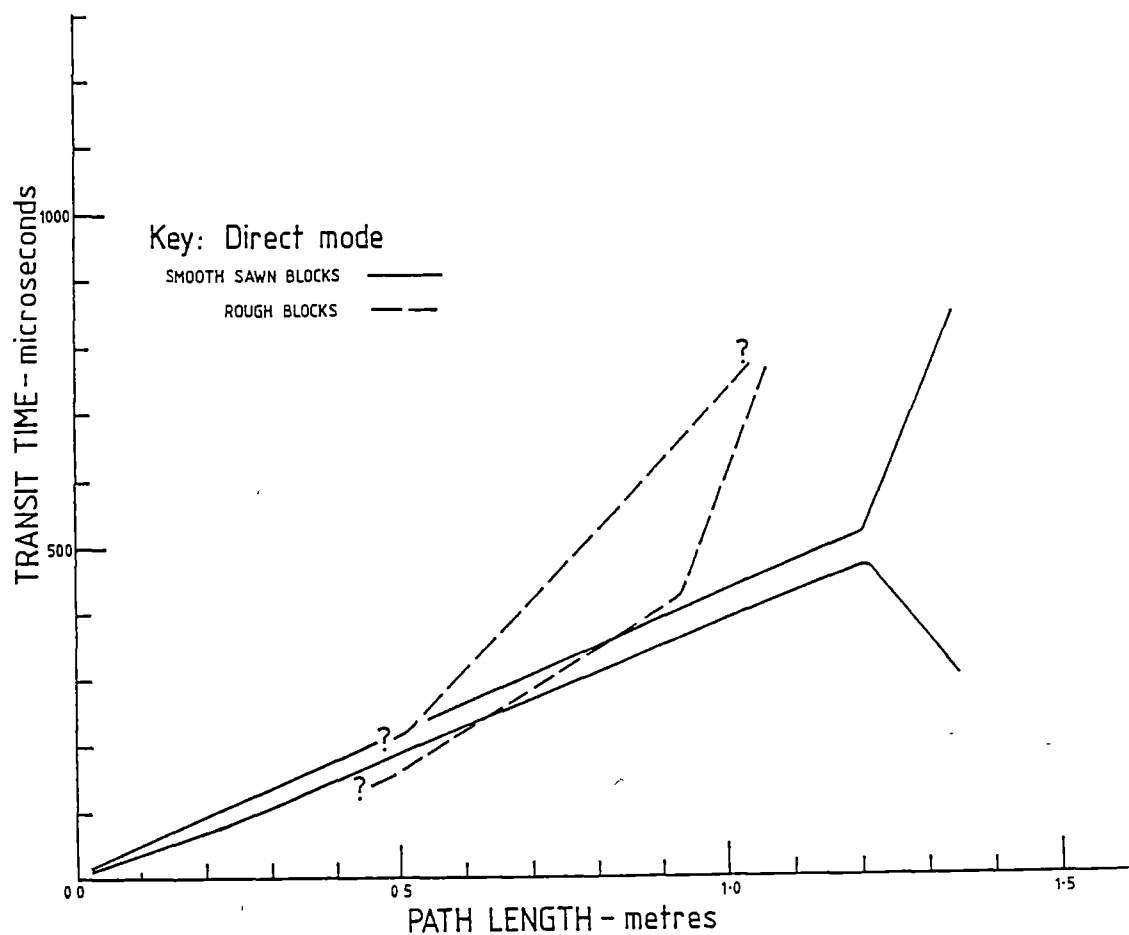


Figure (5.3) Transit Time vs Path Length: Direct Mode Measurements

Envelopes based on Fig. (5.2) data. Envelopes show range of direct UPV measurements. Note that rough blocks envelope is based on only a few data points - the envelope would undoubtedly be even larger with more data.

Several anomalous results - both UPVs too high and too low - were obtained on smooth sawn blocks at path lengths greater than about 1.2 metres. Within the framework of the work done it was not possible to explain these anomalies, but possible explanations include:

- a) As-yet unrecognised effects on UPV transmission in large blocks;
- b) Inhomogeneities in the sandstone. The longer the path length, the more effect inhomogeneities are likely to have on measured UPV (because more inhomogeneities are likely to be encountered in longer path lengths).

In contrast to smooth blocks, direct UPV measurements on rough blocks gave widely varying and unreliable results. As can be seen from Figure (5.3), results obtained varied from results closely similar to those obtained on smooth blocks, to results indicating much slower UPVs than those obtained on smooth blocks. It is significant that very few results were obtained giving faster UPVs than those obtained on smooth blocks.

Since the stone within the rough blocks must be the same as that within smooth blocks, the only possible cause of this great variation in rough block results compared with smooth sawn block results must lie in the condition of the actual surface spot to which the PUNDIT transducers are applied.

The use of hand-held grinders can sometimes yield slightly uneven ground surfaces, due to holding the grinder at different angles. This results in spaces between the transducer heads and the stone, giving poor acoustic coupling and slower measured UPV (as discussed in Section 5.2).

The solution to this problem is to couple the transducers to rough blocks by setting them in plaster of Paris, epoxy resin or cement mortar.

5.3.3 Semi-direct UPV measurements, smooth-sawn and rough blocks

Figures (5.4) and (5.5) illustrate the results obtained by semi-direct testing of smooth sawn and rough blocks. The same data is used for both figures. Points joined by lines in Figure 5.5 are sequences of measurements made on sawn blocks by progressively stepping out one transducer to give progressively longer path lengths through the same homogeneous stone mass.

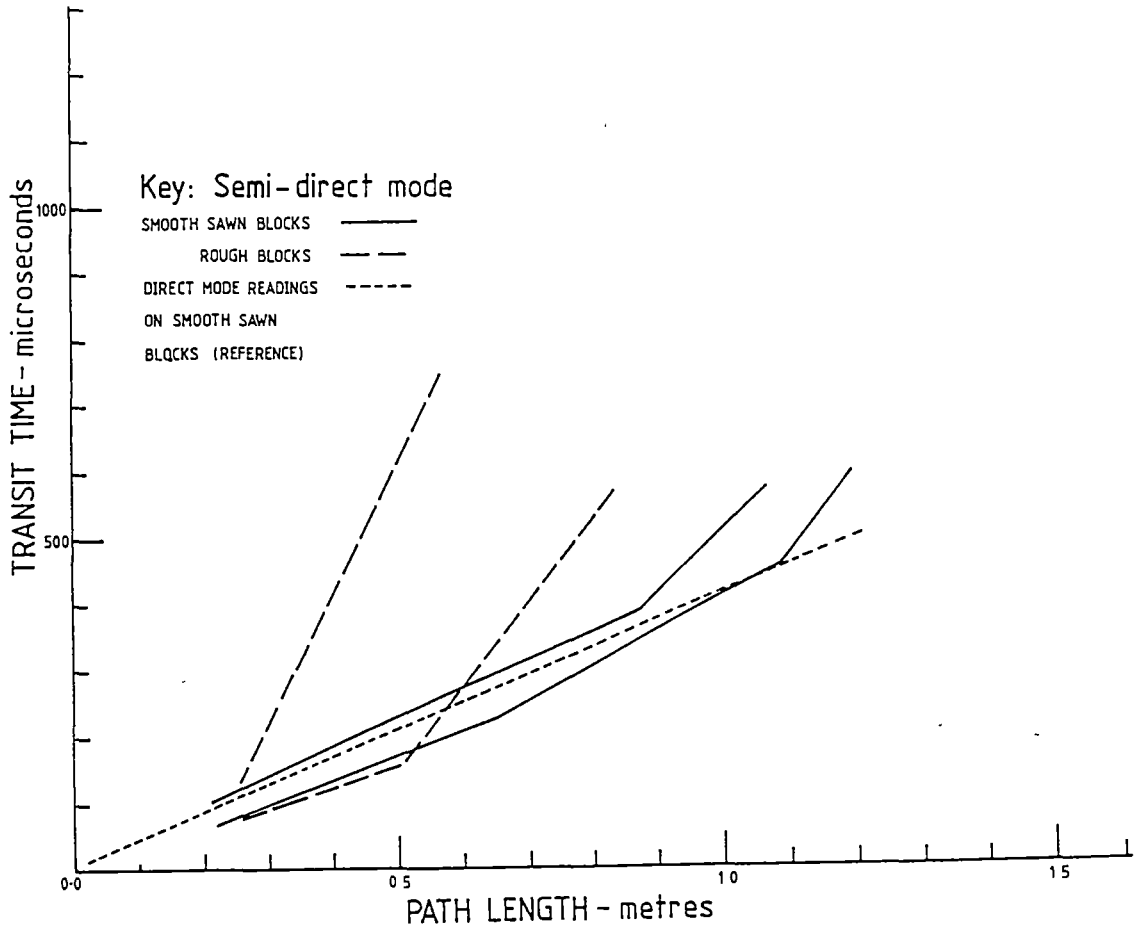


Figure (5.4) Transit Time vs Path Length: Semi-direct mode measurements

Envelopes based on Fig. (5.2) data. Envelopes show range of semi-direct UPV measurements with Direct mode readings on smooth blocks ("True UPV") for comparison. With further data, rough block envelope would probably be even larger.

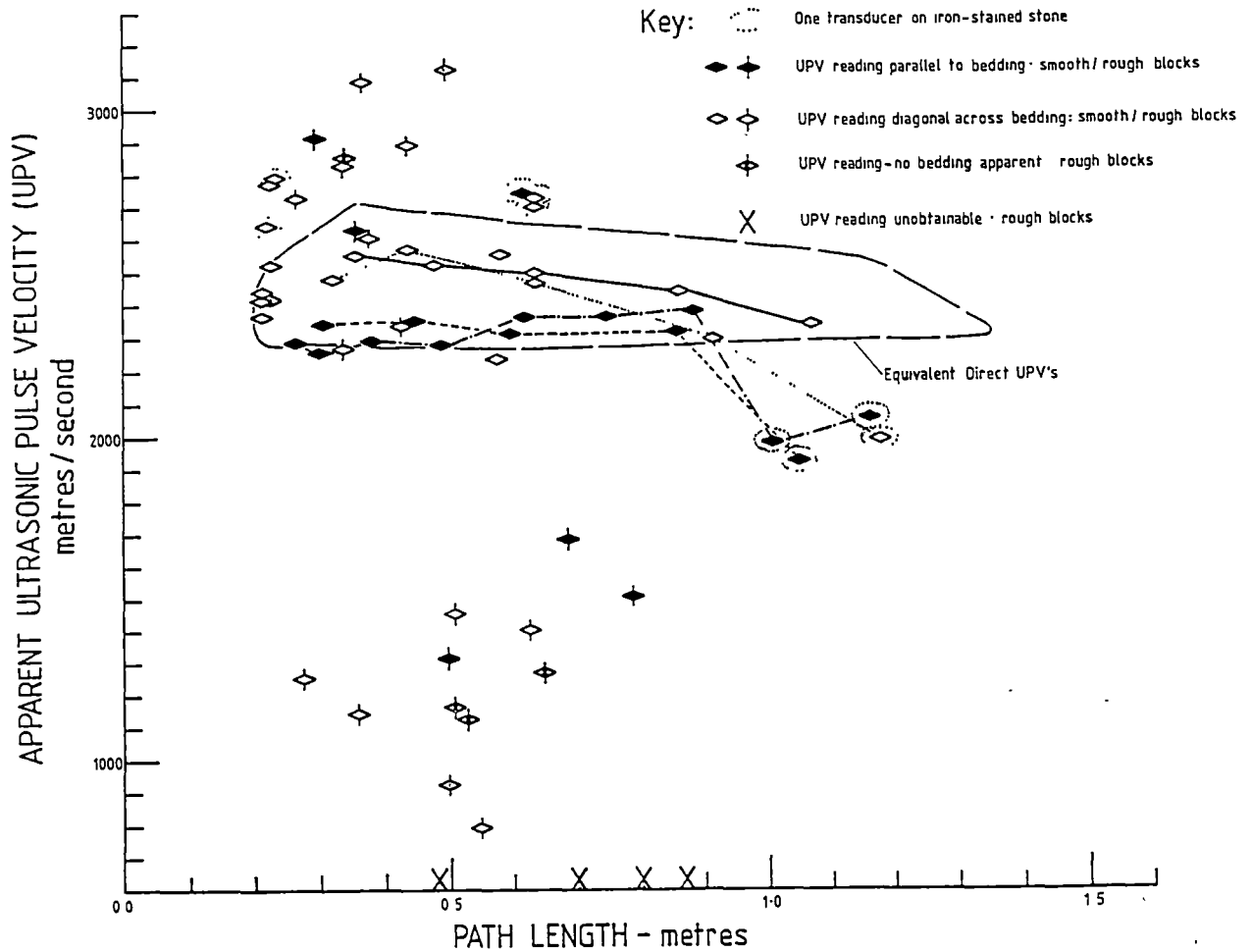


Figure (5.5) Ultrasonic Pulse Velocity (UPV) vs Path Length:- Semi-direct mode on smooth and rough blocks

All stone types tested. Connected data lines represent stepped out measurements in a line on single blocks of Nunamara stone. Direct UPV envelope is data from smooth sawn Nunamara blocks only (individual data points omitted, but see also Fig. 5.3), but Linden/Tea Tree stones would give similar envelopes.

Figure (5.5) clearly demonstrates that, up to path lengths of about 0.9 metres, semi-direct UPV measurements on smooth sawn blocks fall in the same range as direct UPV measurements on the same stone, and moreover up to that maximum path length measured UPV remains reasonably constant with varying path lengths.

At least up to 0.9 metres path length, then, semi-direct measurements are reliable indicators of UPV for smooth sawn blocks. This results from the fact that, like direct measurements, semi-direct measurement involves measurement of signals moving directly through the body of stone from one transducer to the other. The only difference is that the signal measured is not that being propagated normal to the transmitting transducer face, but rather a somewhat weaker signal resulting from scattering of the sonic energy at an angle to the transducer face.

In the present tests, the only semi-direct smooth-block measurements which fell outside the range of the equivalent direct UPV measurements were measurements where at least one transducer head rested on an iron-stained part of the sandstone block. The anomalies are thus explained as resulting from the differing UPV of iron-stained portions of sandstone.

Since this last problem applies to all but two of the measurements made at path lengths greater than 0.9 metres, on the available data it is not possible to be sure how UPV measurements on non-ironstained rocks would behave at greater path lengths. Since even direct measurements seem unreliable over 1.2 metres, however, it is probable that 0.9 metres is close to the upper limit for semi-direct measurement in these types of sandstone.

Nearly all semi-direct measurements on rough blocks gave anomalous results outside the range of direct UPV measurements for those sandstones. In some cases anomalously fast UPVs were obtained, while in the majority of cases anomalously slow UPVs were obtained. In some cases, no reading at all could be obtained of path lengths as short as 0.5 m.

These anomalously slow results are, at least partially, attributed to the same causes as the anomalously slow direct measurement, on rough blocks discussed in the previous section (5.3.2).

The causes of the anomalously fast semi-direct results in rough blocks are undetermined.

5.3.4 Indirect UPV measurements, smooth-sawn and rough blocks

Figures (5.6), (5.7) and (5.8) illustrate the results obtained by indirect testing of smooth-sawn and rough blocks.

Figure (5.7) illustrates the results obtained by stepping out to progressively larger indirect path lengths on single surfaces of smooth sawn blocks. A quite distinctive pattern of UPV measurements is obtained.

At very short path lengths, abnormally fast UPV measurements are obtained (fast with respect to the 'true' UPVs measured directly for the same blocks - see Figure (5.7)). As path length increases, the measured UPV steadily slows - sometimes in a somewhat irregular manner - until at path lengths of greater than about 0.7 to 1.0 metres the measured UPV becomes a constant at about half the UPV measured directly on the same blocks. At path lengths varying between 0.9 and 1.5 metres, the signal strength becomes too low for any measurement to be made.

At no stage does indirect UPV measurement yield a consistent UPV which is the same as the 'True' P-wave UPV measured directly on the same sandstone blocks.

The explanation of this indirect UPV behaviour is unclear, and would need further research to elucidate. The important thing is that a recognisable and repeated pattern is evident. Some comments on the possible causes of this indirect UPV behaviour can be made, however.

The abnormally high UPV values obtained at short (less than 0.3 metre) path lengths probably result from distorting 'near-source effects', together with inaccuracies resulting from measuring path length between the centres of the transducer heads. At larger path lengths this latter produces negligible inaccuracies, but at short path lengths the difference of about 0.05 metres between measuring between head centres and the two closest edges of the heads can make a significant difference.

The continuing decrease in measured UPV at intermediate (about 0.3 to 0.7-1.0 metre) path lengths is difficult to explain. If, as theory seems to predict, one were measuring P-wave energy scattered along the surface, one would expect a constant UPV at differing path lengths, and one would expect that UPV to be similar to the UPV measured directly on the same blocks. These conditions are not fulfilled.

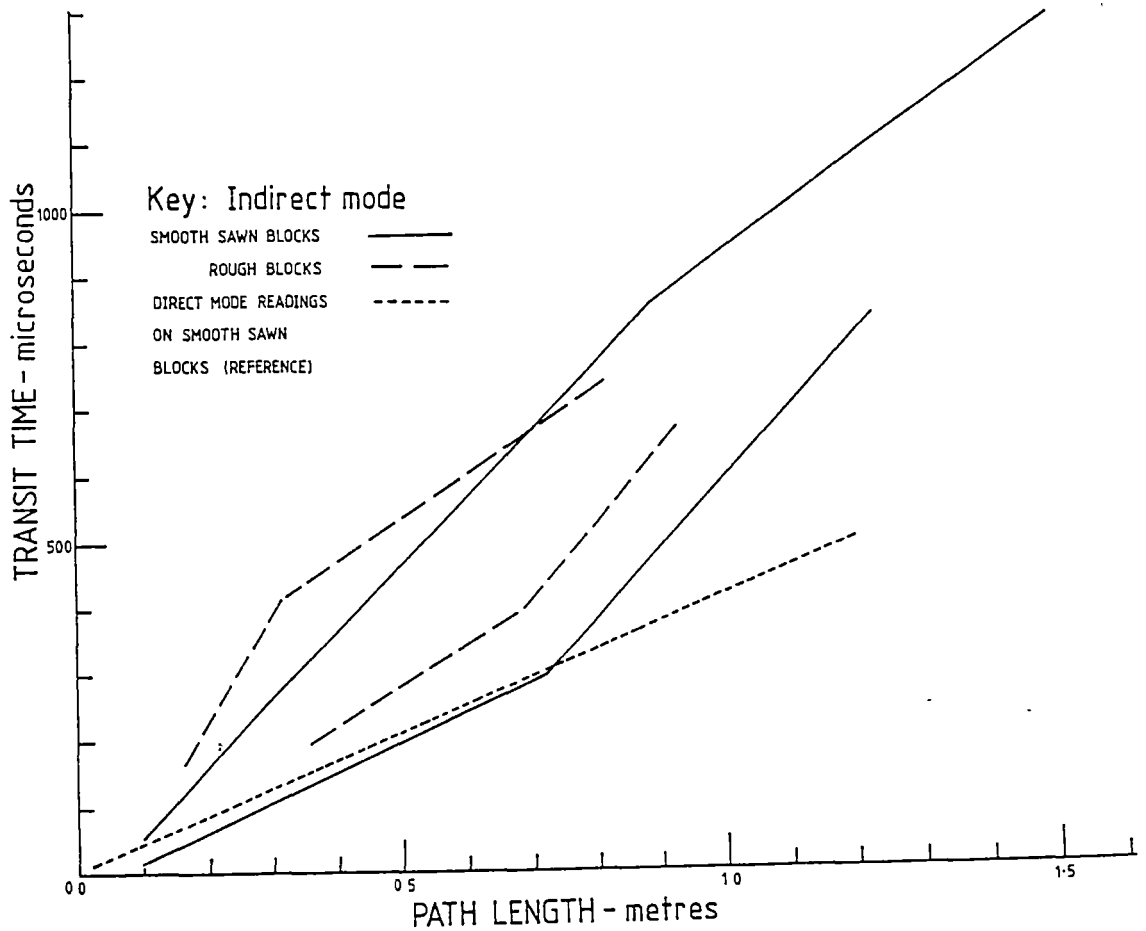


Figure (5.6) Transit Time vs Path Length: Indirect mode measurements

Envelopes based on Fig. (5.2) data. Envelopes show range of Indirect UPV measurements, with Direct mode readings on smooth blocks ("True UPV") for comparison. With further data, rough block envelope would probably be even larger.

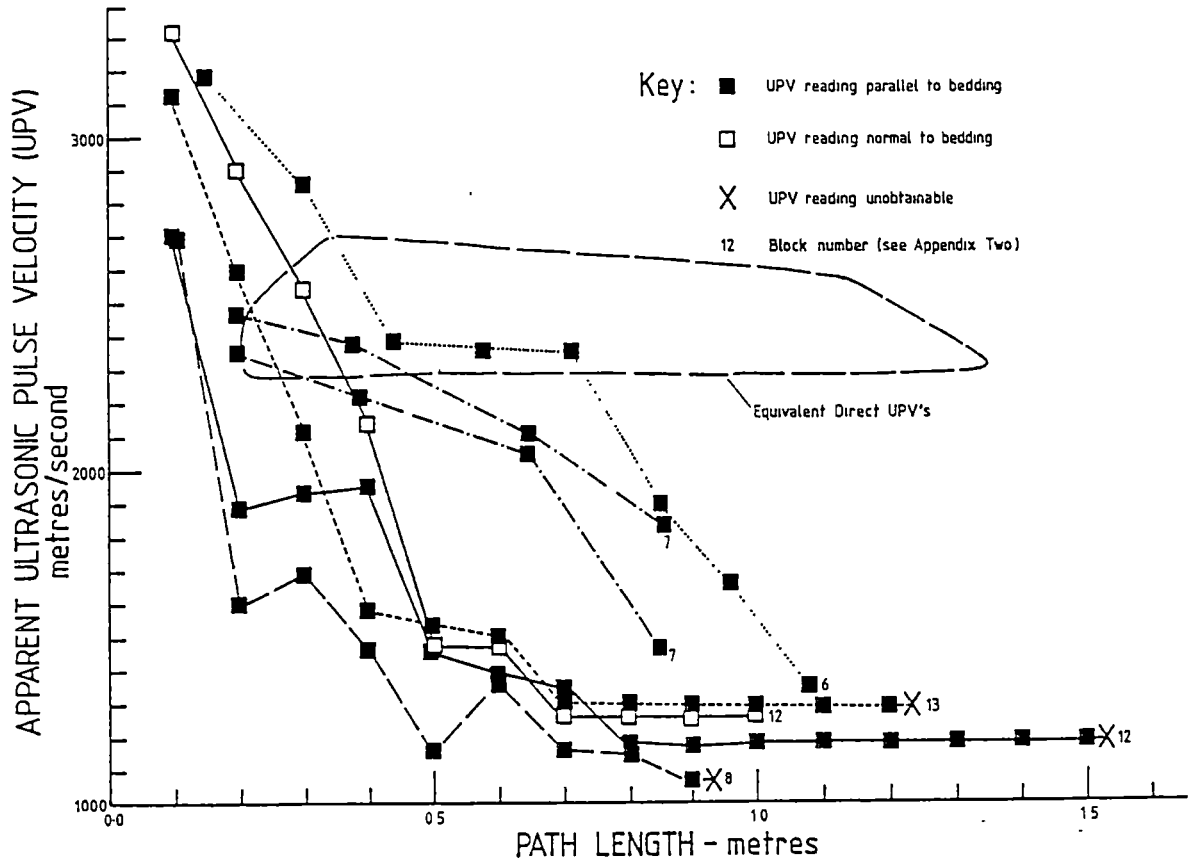


Figure (5.7) Ultrasonic Pulse Velocity (UPV) vs Path Length:- Indirect mode on smooth sawn blocks

All Nunamara stone. Connected lines of data points represent stepped out measurements on a single surface. Direct UPV envelope represents direct mode data from the same group of blocks, with individual data points omitted (See also Fig. 5.3).

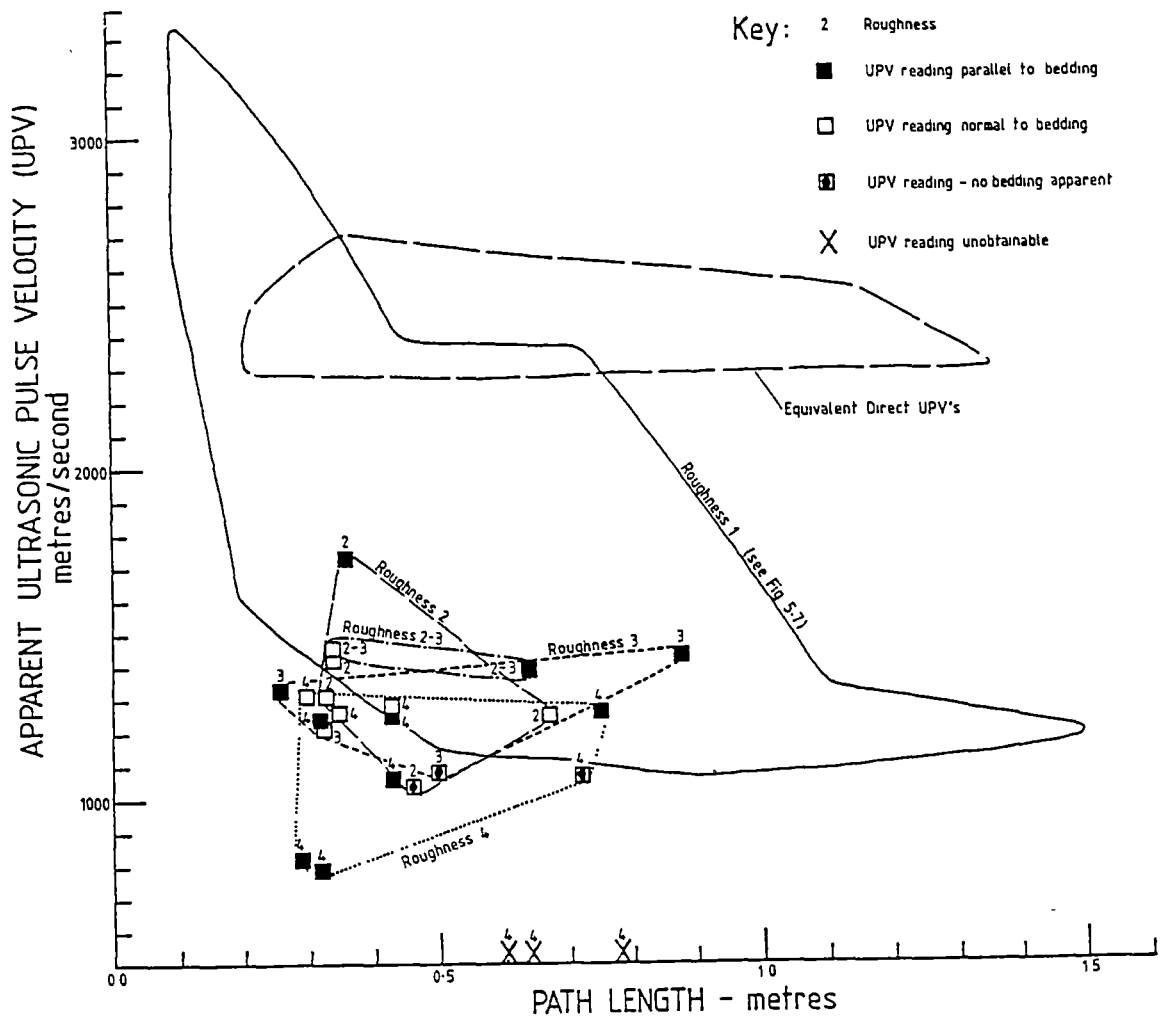


Figure (5.8) Ultrasonic Pulse Velocity (UPV) vs Path Length:- Indirect mode on rough blocks.

Nunamara and Linden Stone. Envelopes shown for data points of differing roughness (See text). Points omitted from Roughness 1 envelope (which comprises all data in Fig. 5.7). Direct UPV envelope is data from smooth sawn Nunamara blocks only (individual data points omitted, but see also Fig. 5.3), but Linden Stone has similar properties and would give a similar Direct UPV envelope.

28.

An alternative hypothesis that 'indirect' measurements are actually measuring P-waves reflected internally from the opposite side of the block was modelled, and failed to yield the correct answers.

The explanation for the steady decrease in measured UPV with increasing path lengths remains unclear.

The final constant UPV measured at path lengths of greater than about 0.7 to 1.0 metres is of the correct magnitude, compared to directly measured P-wave UPV for the same sandstone blocks, to be a true surface (Rayleigh) wave, if we assume a Poisson's ratio of 0.25 for the sandstone (Leonie Jones, pers.comm. 1985). The PUNDIT apparatus has no facility for measuring the sense of particle motion in the sonic vibrations it measures, and thus cannot distinguish between P-waves and Rayleigh waves. Note that the PUNDIT manual assumes - and we now see this may be erroneous - that only P-wave energy is involved in indirect measurements.

It would appear that once the small amount of P-wave energy being transmitted superficially in the blocks becomes sufficiently scattered to fall below the limits of intensity which the PUNDIT can detect, then the first measurable arrival becomes the surface Rayleigh waves. The Rayleigh waves are the only measured waves in the indirect mode which have a consistent relationship (of about half) to the 'True UPV' measured directly on the same blocks.

As with direct and semi-direct measurements, indirect measurements on rough-surfaced blocks yield anomalous UPV values. As shown on Figure (5.8), Indirect UPV measurements on rough-surfaced blocks yield UPV values which are consistently slower than values obtained on smooth-surfaced blocks of the same sandstone types. In addition, on rough blocks it is only possible to make indirect measurements over shorter path lengths than on smooth blocks - the signal appears to become too weak to measure at path lengths varying from about 0.6 to 0.9 metres.

This behaviour can be in part ascribed, as for direct and semi-direct rough-block measurements, to imperfectly flat measuring spots, a problem which can be corrected by embedding the transducer heads in suitable coupling materials.

In addition to this problem, however, rough surfaces introduce another problem to indirect UPV measurement which does not apply to direct and semi-direct measurements. Since the signal being measured is travelling along the surface itself, it is likely that the roughness of the surface between the transducer heads will affect the signal, and this does appear to be the case.

For the purposes of this investigation, four degrees of surface roughness were defined, as follows:

- 1) Sawn flat and smooth: no surface irregularities at all.
- 2) Slightly rough: surface irregularities less than 0.01 metres deep, surface flat or only slightly curved.
- 3) Intermediate roughness: surface irregularities 0.01 - 0.02 metres deep.
- 4) Very rough: surface irregularities greater than 0.02 metres deep.

The surfaces of the various rough blocks measured in indirect mode were classified in this way. On Figure (5.8) the results are plotted, with the roughness of each surface measured indicated. There is a rather broad shift to lower measured UPV with increasing surface roughness, although the pattern is not a strong one.

It is probable that surface roughness both increases the scattering of the sonic signal, thereby shortening the path lengths over which surface signals can be measured and also creates, in effect, a longer surface distance for signals to travel over, so that the real path length will be longer than the measured ('straight line') path length, resulting in measured UPVs appearing to be slower than UPVs over comparable measured path lengths on flat smooth surfaces.

Section SIX

CONCLUSIONS - USEFULNESS OF UPV MEASUREMENT AND RECOMMENDED PROCEDURES

6.1 Summary of Conclusions

This investigation of Ultrasonic Pulse Velocity measurement was directed towards:

- a) determining whether and in what degree UPV measurements obtained from Tasmanian building sandstone specimens correlate with the major properties of those sandstones as relevant to durability.
- b) determining whether and in what degree UPV measurements obtained vary with the various measuring conditions and techniques likely to be employed in a practical situation (i.e., smooth and rough blocks, in direct, semi-direct or indirect mode).

The major conclusions drawn are as follows:

- a) In most situations, the first-arrival sonic energy whose velocity is being measured is P-wave (body wave) vibrations identical to those involved in larger scale seismic phenomena. In indirect measurement, however, true surface waves (Rayleigh waves) appear to be involved.
- b) Direct-mode measurements in the laboratory show that measured UPV has no significant correlation with either smectite (swelling clay) or total clay content of the sandstone, taken by themselves.

However, correlating in a logarithmic fashion, UPV has a 47.99% correlation with the Point Load Strength Index (tensile strength) of sandstone. That is, nearly half of the measured UPV of a sandstone is determined by the strength of the stone.

Although porosity by itself has only a 23% logarithmic correlation with UPV, the combination of strength (S) and porosity (P), in the form S/P , has a 50.8% logarithmic correlation with the measured UPV of the sandstone.

UPV measurement on Tasmanian building sandstones is therefore a useful tool in that it gives a better than 50% correlation with two of the most important parameters determining durability, strength and porosity.

However, UPV measurement cannot give a full assessment of stone durability, since it can give no independent assessment of swelling clay content, as also because it cannot give a correlation of much better than 50% with strength and porosity.

- c) Direct-mode UPV measurements on smooth sawn blocks, at path lengths of up to 1.2 metres, give consistent and reliable results. UPV measurements so obtained are regarded as the 'True UPV' of the sandstone in question.
- d) Semi-direct mode UPV measurements on smooth sawn blocks, at path lengths of up to 0.9 metres (and possibly more) give consistent and reliable UPV measurements which are identical to values obtained by direct-mode measurements, and can also be taken as the 'True UPV' of the stone.
- e) Indirect mode UPV measurements on smooth sawn blocks give varying and unreliable results at path lengths up to between 0.7 and 1.0 metres. At greater path lengths a consistent and reliable UPV is measured until the signal strength becomes too faint to measure (at between 0.9 and 1.5 metres). This consistent signal appears to be a Rayleigh wave and has a UPV of approximately half the 'True UPV' (i.e. P-wave UPV measured directly or *semi*directly) of the same stone blocks.

It is not known whether this Rayleigh wave:P-wave UPV ratio of 1:2 would hold for sandstones having significantly different properties. The relationship is likely to be reasonably consistent for most Tasmanian sandstones, however, since their strength and porosity do not generally vary radically.

- f) At Path lengths greater than 1.0 to 1.2 metres, all UPV measurement modes can begin to give anomalous results.
- g) Rough stone surfaces provide difficulties for UPV measurement in any mode, whether direct, semi-direct or indirect. In order to obtain reliable 'True UPV' measurements by direct or semi-direct means, perfectly flat and smooth contact spots for the transducer heads must be prepared (which is difficult to do in the field), or the transducer heads must be bonded to the stone surface with plaster, mortar or epoxy resin (which is time consuming, and was not done in this study).

Even with the above preparations, it may often be impossible to obtain meaningful UPV measurements in the indirect mode on rough surfaces. This is because the dissipation and distortion of the surface signal by the irregularity of the surface will yield inconsistent and unpredictable results, and moreover will probably dissipate any signal before the path length is reached at which a consistent Rayleigh wave velocity can be measured.

Unfortunately, this means that it will often be very difficult or impossible to obtain useful UPV data from a rough quarry face, unless there are suitable corners in the face to take semi-direct measurements on.

In addition, it must be remembered that if the surface measured is weathered or case hardened, any indirect UPV measurement will reflect the condition of the surface only, not the body of rock beneath it.

6.2 The value of UPV measurement

Ultrasonic Pulse Velocity measurement does not yield precise values for the strength and/or porosity of sandstone, since it does not correlate 100% with those properties, and it does not yield any values for swelling clay (or total clay) content. UPV therefore is not so much a tool for precisely determining other particular properties of a stone, but rather is a property in its own right, which can broadly be thought of as a resultant of a number of other sandstone properties of relevance to durability.

The value of UPV measurement is that it will give an idea of the strength and porosity of a stone, and also it will quite sensitively distinguish between the better and worse quality stones in a suite of related blocks.

However, independent tests of smectite (swelling clay) content still need to be carried out by the traditional laboratory methods. It is fortuitous, perhaps, that the X-ray diffraction test for smectite is the simplest and least time-consuming of all the sandstone laboratory tests described in Sharples *et al.* (1984).

UPV measurement is most easily and quickly applied as a quality-control procedure for use on sawn blocks prior to their being placed in a building. The technique also ought to be applicable to testing stones already in buildings to identify stones most likely to fail (although this was not tried in the present study).

Unfortunately, the method is not as easily applicable to the pre-quarrying assessment of in situ stone, or the pre-sawing assessment of rough blocks, as was originally hoped. Such assessment is possible, but takes more time and preparation than might have been hoped.

On the other hand, if diamond-drilling of a quarry were undertaken, the UPV method would be an admirably efficient way of testing the core samples in detail.

6.3 Recommended Procedures

The use of Ultrasonic Pulse Velocity measurement can be used to assess the quality (i.e., durability) of a suite of sandstone specimens, in detail, much more rapidly than could be done by the method of comprehensive sampling and laboratory testing. However the UPV method cannot generally be used in isolation.

It is recommended that for any suite of sandstones it is desired to test (e.g., a quarry, a group of blocks taken from a particular quarry, or a group of blocks in a building), a small selection of samples should be collected and subjected to standard laboratory tests for strength, porosity and clay content. This is particularly important for clay content, which UPV measurements will not give any indication of.

With these few laboratory results as references, the PUNDIT can then be rapidly applied to large volumes of stone (commencing with the sampled parts). Variations in UPV can be related to the reference samples to give an accurate indication of quantitative variations in strength and porosity.

Less accurate quantitative estimates of strength or strength/porosity can be obtained without taking any reference samples (reference to figs. (4.2) and (4.6) indicates the range of strength and strength/porosity corresponding to given UPVs in Tasmanian sandstones), but in all cases it is necessary to process some small samples for clay content, using X-ray diffraction. Given the importance of swelling clay content in the durability of Tasmanian building sandstones, XRD testing for clays is essential.

The following is a listing of the major practical situations in which UPV measurement could be used, with comments on each (see Section 5 for maximum and optimum path lengths to measure over):

34.

Situation	Best possible mode of measurement	Couplant Required	Comments
Quarry or Outcrop - rough surface only	Indirect	-	Worthwhile results unobtainable (see section 5.3.4)
Quarry or Outcrop - rough surface with corners	Semi-direct	Probably need plaster, epoxy or mortar	Time-consuming but valuable results obtainable. Beware weathered zones
Rough quarried blocks	Direct (semi-direct may also be useful)	Probably need plaster, epoxy or mortar	Time consuming but valuable results obtainable
Smooth sawn blocks	Direct (semi-direct & indirect may also be useful)	Grease (e.g. vaseline)	Rapid, accurate. <u>This is the best application for UPV measurement.</u>
Old blocks in buildings	Direct (but often only semi-direct or indirect will be possible due to block location in building)	Grease (e.g. vaseline), or else plaster, epoxy or mortar, depending on condition and finish of stone surface	Could be rapid or slow, depending on stone surface condition and couplant required

Section SEVEN

REFERENCES

- ALLAN, M. & LAWRENCE, D. 1972. Geological Laboratory Techniques. Arco Publishing Co., Inc., New York, 335 p.
- BELL, F.G., 1983(a). Fundamentals of Engineering Geology. Butterworth & Co., U.K.
- CARMICHAEL, R.S. (ed.), 1982. Handbook of Physical Properties of Rocks, Vol. II. [P & S wave seismic velocities in various rock types - lab data]. CRC Press Inc., Boca Raton, Florida.
- CLARK, S.P. (ed.), 1966. Handbook of Physical Constants. Geol.Soc. America, Memoir 97.
- GRIM, R.E., 1968. Clay Mineralogy. McGraw-Hill, Inc., New York, 596 p.
- JUMIKIS, A.R., 1979. Rock Mechanics. Series on Rock and Soil Mechanics, Vol. 3, (1978/79) No. 5. Trans Tech. Publications, Rockport, MA, USA, 356 p.
- SENGUPTA, M., 1975. A new method of evaluation for dimension stone from diamond-drill core. CIM Bulletin, July 1975.
- SHARPLES, C., GREEN, D.C., SPRATT, P., AND BANKS, M., 1984. Tasmanian Building Sandstones. Unpubl. Rept. Tas. Dept. Mines, prepared for National Estate, Tasmania. 2 volumes.
- SITTIG, M., 1981. Handbook of Toxic and Hazardous Chemicals. Noyes Publications, New Jersey, USA.
- STACEY, F.D., 1969. Physics of the Earth. John Wiley & Sons, Inc., New York, 324 p.
- TUCKER, R.H., COOK, A.H., IYER, H.M., STACEY, F.D., 1970. Global Geophysics. The English Universities Press Ltd., London, 199 p.
- WILLIAMS, R.B.G., & ROBINSON, D.A., 1983. The effect of surface texture on the determination of the surface hardness of rock using the Schmidt hammer. Earth Surface Processes and Landforms, Vol. 8, p. 289-292.
- WINKLER, E.M., 1973. Stone: Properties, Durability in Mans Environment. 230 p, Springer-Verlag, Wien-New York.
- YEN, T.F., & CHILINGARIAN, G.V., (eds), 1976. Oil Shale. Elsevier, Amsterdam, 292 p.

APPENDIX ONE

LABORATORY ULTRASONIC PULSE VELOCITY MEASUREMENTS

Data obtained, presented as averages of
values obtained for each specimen

Other detailed information on specimens is
presented in Sharples et al (1984)

LABORATORY TESTS - DATA OBTAINED

Specimen	Ultrasonic Pulse Velocity (m/sec) (av. direction) (UPV)	Dry Point Load Strength Index (MPa, av. all directions) (S)	Effective Porosity Vol. % (P)	Durability in Salt Test (Vol % loss after 10 cycles)	Detrimental* clay content Vol. % (C)	Total Clay Content (vol. %)	$\frac{S}{P+C}$	$\frac{S}{P}$
TT7	2738	1.23	10.54	-	1.43	13.0	0.103	0.117
TT6	2837	1.12	11.09	-	1.3	13.0	0.090	0.101
TT8	2950	0.49	9.89	-	3.12	12.0	0.038	0.05
LPO3	2876	1.56	10.40	3.0	4.59	17.0	0.104	0.15
LPO4	2838	1.71	8.9	-	1.87	17.0	0.159	0.192
Etna 1	2704	1.18	10.76	25.0	1.44	18.0	0.097	0.11
Etna 2	2137	0.26	13.01	100.00	1.1	22.0	0.018	0.02
Etna 3	2629	0.8	12.06	14.0	0.0	15.0	0.066	0.066
TT5	2974	1.02	10.36	0.0	2.0	13.0	0.083	0.098
TT4	2875	0.83	8.69	-	4.34	14.0	0.064	0.096
TT3	2625	1.08	12.94	-	4.94	13.0	0.060	0.083
KN1	2982	2.23	10.13	-	0.0	29.0	0.220	0.220
FB1	3262	2.11	8.97	7	0.0	23.0	0.235	0.235
Braemer 1	2022	0.4	13.04	10	0.0	18.0	0.031	0.031
N1	2338	1.19	10.66	3	0.0	25.0	0.112	0.112
CON 1	2552	1.75	9.07	5	0.0	30.0	0.193	0.193
PA1	1897	0.25	17.25	100	21.44	32.0	0.006	0.014
PA2	1972	0.22	13.03	-	7.28	14.0	0.011	0.017
PA3	2166	0.08	14.08	-	10.75	25.0	0.003	0.006
PA4	3072	1.99	10.11	4	12.0	12.00	0.090	0.197
PA5	2742	0.31	12.39	5	7-	20.0	7-	0.025
SM1	2178	0.19	15.48	-	24.98	45.0	0.005	0.012
Cobb 1	2255	0.64	12.84	37	1.5	15.0	0.045	0.050
Lach 1	3006	0.98	9.70	10	0.0	26.0	0.101	0.101
Cam 1	2121	0.31	12.80	14	3.42	19.0	0.019	0.024
WW1	2088	0.91	12.82	13	0.0	21.0	0.071	0.071
MHQ1	2355	0.17	16.05	5	2.24	28.0	0.09	0.011
MM1	2606	1.51	14.61	16	0.0	23.0	0.103	0.103
Oak1	1576	0.10	13.58	100	0.0	32.0	0.007	0.007
Oak2	2837	1.67	13.28	8	0.0	28.0	0.126	0.126
L1	3020	1.82	9.11	3	4.2	14.0	0.137	0.200
L2	2575	1.11	11.83	5	3.25	13.0	0.074	0.094
Cop 2	2910	0.71	8.81	6	0.0	14.0	0.081	0.081
Riz 1	2223	0.90	16.35	6	3.36	24.0	0.046	0.055
MH1	3032	2.46	10.15	4	0.0	23.0	0.242	0.242
V1	3296	1.29	10.47	3	0.0	13.0	0.123	0.123
V2	2645	0.47	11.7	8	7.48	17.0	0.025	0.040
V3	3008	1.03	9.79	-	1.04	8.0	0.095	0.105
Trinity 1	2497	0.55	16.38	-	9.52	28.0	0.021	0.034
Trinity 2	2600	0.83	17.11	3.0	9.6	48.0	0.031	0.049
OM1	3158	2.05	12.16	-	some?	-	-	0.169
K1	2855	2.42	10.42	4.0	3.42	38.0	0.175	0.232
Ross 1	2527	0.34	15.86	23.0	0.0	33.0	0.021	0.021
Ross 2	2865	0.91	17.09	-	0.0	27.0	0.053	0.053
Ross 3	2448	0.43	15.89	12.0	0.0	35.0	0.027	0.027
Ross 4	3454	1.27	13.71	-	0.0	30.0	0.093	0.093
Ross 6	3045	0.68	13.95	7.0	0.0	27.0	0.049	0.049
Ross 7	2755	0.55	15.92	-	0.0	27.0	0.035	0.035
NSW1	2162	1.04	10.37	6.0	0.0	-	0.100	0.100

* Only smectite and mixed layer illite/smectite counted as 'detrimental' (swelling) clay; vermiculite not counted.

APPENDIX TWO

FIELD ULTRASONIC PULSE VELOCITY MEASUREMENTS

Field data sheets

PUNDIT TEST

Date :- 31/7/85

Test Locality:- Dunns Yard

Test location (within locality):- Block 1 - London

General condition of test surface/rock body:- Fresh

Test orientation ^①:- see diagram

Note - semi-direct path length is straight-line dist. between test points.

Comments, Fractures, etc: no fractures

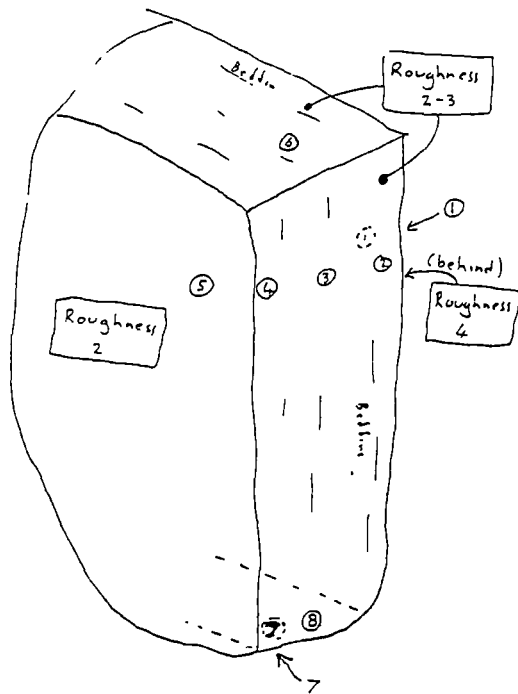
	Test between and	Transducer head size	Condition of Test points	Test method	Path length (L) metres	Transit time (T) μ sec	Ultrasonic pulse velocity (V) $V = \frac{L}{T}$	
doing up to bedding	①	⑤	Small	Fresh, ground Flt	Direct	0.47	153	3072 m/sec
	②	④	Small	"	Indirect	0.34	235	1447 m/sec
	①	③	Small	"	Semi-direct	0.37	120	3083 m/sec
	③	⑤	"	"	Semi-direct	0.27	99	2727 m/sec
bedding	⑥	⑦	"	Fresh, ground Flt, ⑦ - slightly case-hardened	Direct	0.93	435	2138 m/sec
	⑥	③	"	Fresh, ground Flt	Semi-direct	0.30	103	2913 m/sec
	③	⑦	"	"	Semi-direct	0.69	409	1687 m/sec
	③	⑧	"	"	Indirect	0.64	461	1388 m/sec
bedding								
bedding								
bedding								

- ① Orientation of direct line between transmitter/receiver, W.R.T. bedding
- ② Test point numbers (i.e. receiver & transmitter locations & numbers)
- ③ Weathered, fresh & rough, fresh & ground Plot, etc.
- ④ Direct, Semi-direct, indirect.

- ⑥ Specimen no's, location of each spec w.r.t. Test points

Dunn's yard

Block 1 - Linden



PUNDIT TEST

Date :- 7/8/85

Test Locality:- Dennis Yard

Test location (with locality):- Block ② - Linden Stn
(tried previously 2 small heads, couldn't
get good readings)

General condition of test surface/rock body:- Fresh, possibly partly saturated & water

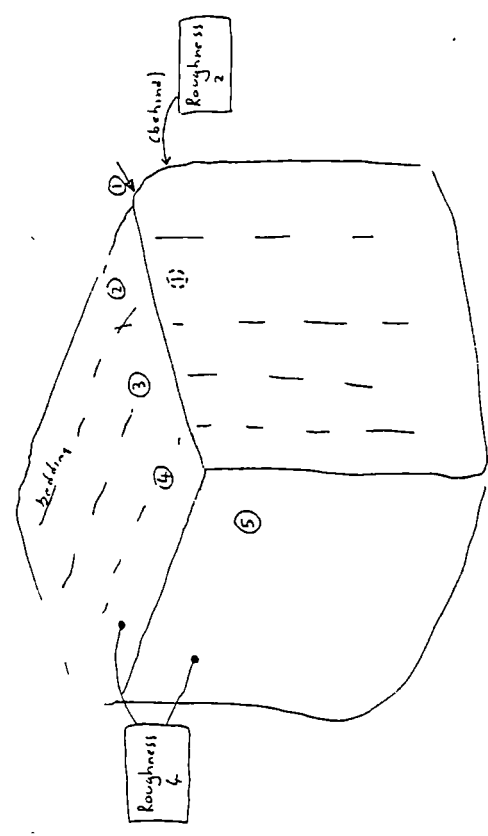
Test orientation ^①:- See diagram

Comments, Fractures, etc: None

[illegible]

- ① Orientation of direct line between transmitter/receiver, w.r.t bedding
- ② Test point numbers (ie, receiver & transmitter locations & numbers)
- ③ Weathered, Fresh & rough, Fresh & ground flat, etc.
- ④ Direct, Semi-direct, indirect.
- ⑤ Separation of transducer heads (ie, test points) in a straight line
- ⑥ Specimen no's, location of each spec w.r.t. Test points

Dunns Yard - Block (2) - Linden Stone



PUNDIT TEST

Date :- 7/8/85

Test Locality:- Dunn, Yard

Test location (with locality):- Linden stone block (Block ③)

General condition of test surface/rock body:- Fresh ~~and free from cracks but a few fine staining~~
block possibly partly saturated by recent rain.

Test orientation ^①:- see diagram

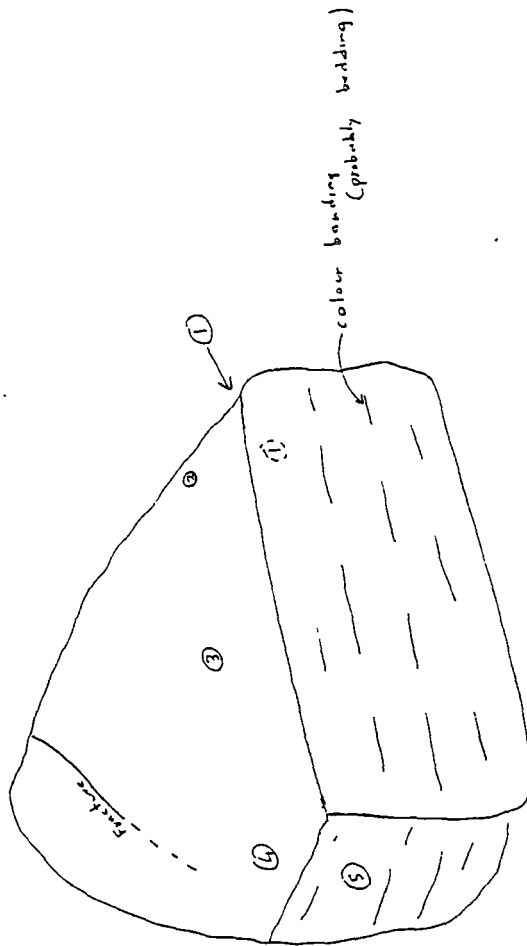
Comments, Fractures, etc: one fracture in block, but away from testing part

Test between and	Transducer head size	Condition of Test points	Test method	Path length (L) metres	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$	
① ⑤	Small	Fresh, ground flat	Direct	1.03	Could not get reading	* small head (not between ②-③, ③-④, ④-⑤ with small head)	
② ③	Small	"	Indirect	0.43	338		1272 m/sec
③ ④	"	"	Indirect	0.32	258		1240 m/sec
④ ⑤	"	"	Semi-direct	0.28	223		1256 m/sec
⑤ ①	"	"	"	"	"		"
② ③	recalibrated large	"	Indirect	0.43	344	1250 m/sec	
③ ④	large	"	Semi-direct	0.63	450	1400 m/sec	
④ ⑤	large	"	Direct	1.03	740	1392 m/sec	
⑤ ①	large	"	Indirect	0.75	596	1258 m/sec	
① ②	large	"	Semi-direct	0.51	351	1453 m/sec	

- ① Orientation of direct line between transmitter/receiver, w.r.t. bedding
- ② Test point numbers (i.e., receiver & transmitter locations & numbers)
- ③ Weathered, fresh & rough, fresh & ground flat, etc.
- ④ Direct, semi-direct, indirect.

- ⑥ Specimen no's, location of each spec w.r.t. Test points

Block (3)



All surfaces roughness 4

PUNDIT TEST

Date :- 8/8/85

Test Locality:- Dennis Yard

Test location (within locality):- Block (4) - Linden Stn

General condition of test surface/rock body:- Fresh, poss partly saturated & water

Test orientation ^①:- see diagram

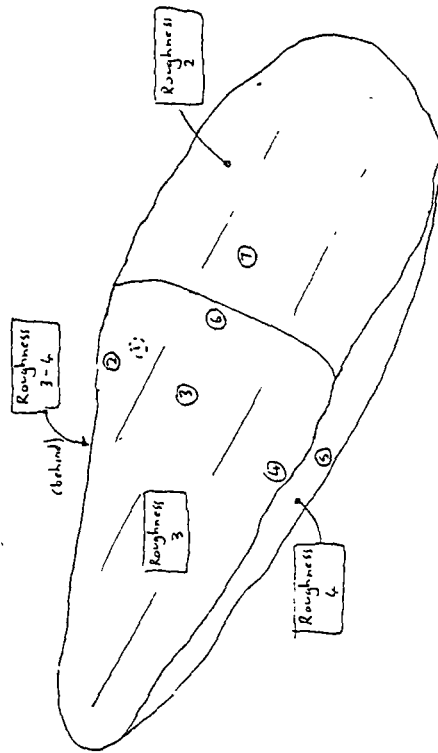
Comments, Fractures, etc: none relevant

[illegible]

- ① Orientation of direct line between transmitter/receiver, WRT. bedding
- ② Test point numbers (i.e. receiver & transmitter locations & numbers)
- ③ Weathered, Fresh & rough, Fresh & ground Flit, etc.
- ④ Direct, Semi-direct, indirect.

- ④ Specimen no's, location of each spec w.r.t. Test points

Block ④ - Linden sandstone - Dunns Yard



PUNDIR TEST

Date :- 22/8/85

Test Locality: Duns Yard

Test location (with location) - Block 5 - Number

General condition of the surface/rock body:- Fresh quarried block

① Test orientation:-

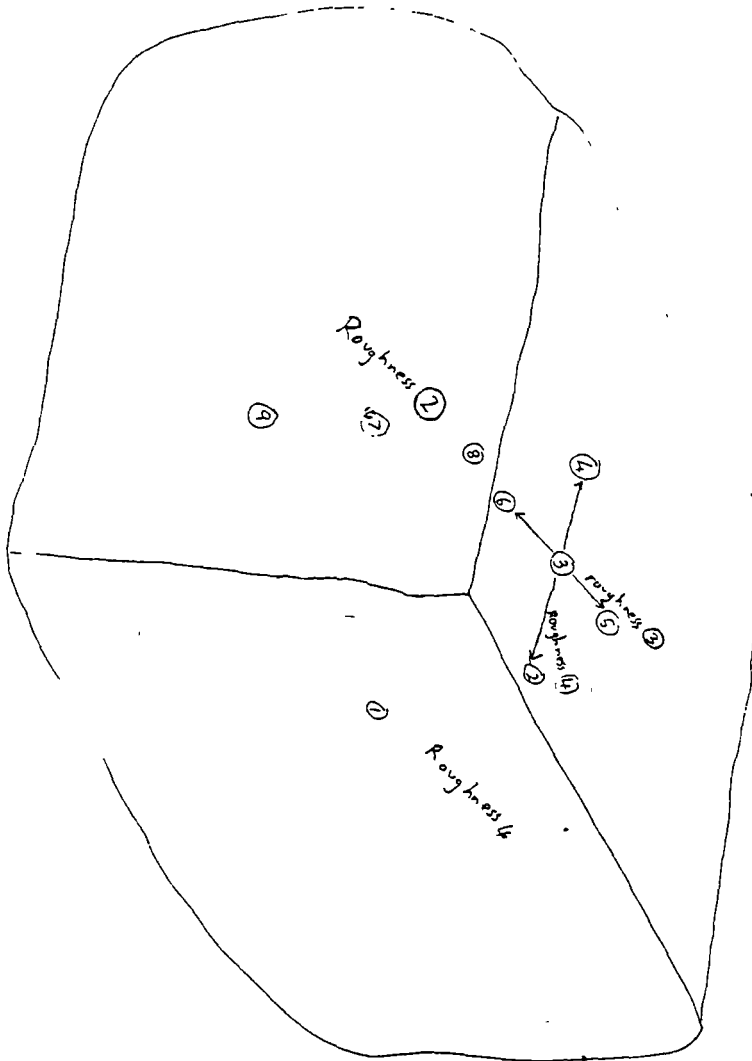
Comments, Fractures, etc:

Test between and	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩
Condition of	Fresh, ground flat	"	"	"	"	"	"	"	"
Test points	Large	"	"	"	"	"	"	"	"
⑥	Semi-direct	Semi-direct	Semi-direct	Semi-direct	Semi-direct	Semi-direct	Semi-direct	Semi-direct	Semi-direct
⑤	Indirect	Indirect	Indirect	Indirect	Indirect	Indirect	Indirect	Indirect	Indirect
Path length (L) metres	0.53	4.72	1.123	1.079	1.156	1.270	1.082	1.031	2.833
③	Transit time (T) / sec	4.72	1.123	1.079	1.156	1.270	1.082	1.031	2.833
Ultrasonic Pulse velocity (V)	$V = \frac{L}{T}$	1123	1079	1156	1270	1082	1031	1031	2833

- ① Orientation of direct line between transmitter/receiver, WRT. bedding
- ② Test point numbers (i.e. receiver & transmitter locations & numbers)
- ③ Weathered, fresh & rough, fresh & ground Flt, etc.
- ④ Direct, semi-direct, indirect.

Block 5 - Mundana Stone - Dunn's Yard

Stone massive - no evidence of bedding direction



PUNDII IESI

Date:-

Test Locality:-

Test location (with locality):- Block 6 C

General condition of test surface/rock body:-

Test orientation^①:-

Comments, Fractures, etc:

	Test between and ^②		Transducer head size	Condition of Test points ^③	Test method ^④	Path length (L) metres ^⑤	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$	
// bedding	(24)	(3)	Large	Fresh, sunn Flat	Semi-direct	1.165	567	2055 m/sec	✓
"	(24)	(18)	"	"	"	1.035	523	1979 "	✓
"	(24)	(17)	"	"	"	0.88	369	2385 "	✓
"	(24)	(19)	"	"	"	0.75	317	2366 "	✓
"	(24)	(6)	"	"	"	0.62	262	2366 "	✓
"	(24)	(20)	"	"	"	0.49	215	2279 "	✓
"	(24)	(16)	"	"	"	0.385	168	2242 "	✓
"	(24)	(21)	"	"	"	0.305	135	2259 "	✓
"	(24)	(6)	"	"	"	0.27	118	2288 "	✓
diag to bedding	(15)	(6)	"	"	"	1.18	544	1987 "	✓
"	(15)	(23)	"	"	"	0.92	401	2294 "	✓
"	(15)	(2)	"	"	"	0.64	4259	2471 "	✓
"	(13)	(23)	"	"	"	0.44	171	2573 "	✓
"	(12)	(7)	"	"	"	0.325	131	2481 "	✓
⊥ bedding		(11)	"	"	direct	0.34	130	2615 m/sec	✓
⊥ bedding		(10)	"	"	direct	0.34	145	2345 m/sec	✓

- ① Orientation of direct line between transmitter/receiver, w.r.t. bedding
 ② Test point numbers (ie, receiver & transmitter locations & numbers)
 ③ Weathered, fresh & rough, fresh & ground flat, etc.
 ④ Direct, Semi-direct, indirect.

- ⑤ Separation of transducer heads (ie, test points) in a straight
 ⑥ Specimen no's, location of each spec w.r.t. Test pos

PUNDIT TEST

Date: 23/8/85

Test Locality: Durin Workshop

Test location (within locality): Block 6

Mina

General condition of test surface/rock body: Fresh sawn block (all surfaces flat & straight)

Munamara
SST.

Test orientation^①: See diagram

Comments, Fractures, etc: none

	Test between and	Transducer head size	Condition of Test points	Test method	Surface Path length (L) metres	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$	
// bedding	① ②	large	Fresh, sawn flat	direct	1.16	457	2538 m/sec	✓
// bedding	① ⑤	"	"	Semi-direct	0.58	247	2348 m/sec	✓
// bedding	② ⑤	"	"	Semi-direct	0.62	226	2743 m/sec	✓
diag to bedding	① ⑥	"	"	Semi-direct	0.585	229	2555 m/sec	✓
diag to bedding	② ⑥	"	"	Semi-direct	0.64	235	2723 m/sec	✓
// bedding	⑦ ⑧	"	"	Indirect	1.08	703	1536 m/sec	✓
// bedding	④ ③	"	"	Indirect	1.08	798	1353 m/sec	✓
diag to bedding	① ④	"	"	Semi-direct	0.58	260	2231 m/sec	✓
diag to bedding	② ④	"	"	Semi-direct	0.64	237	2700 m/sec	✓
// bedding	⑩ ⑪	"	"	Indirect	1.11	715	1552 m/sec	✓
⊥ to bedding	⑥ ⑦	"	"	direct	0.34	144	2361 m/sec	✓
diag to bedding	⑤ ④	"	"	Semi-direct	0.22	93	2366 m/sec	✓
diag to bedding	⑤ ⑧	"	"	Semi-direct	0.24	86	2791 m/sec	✓
⊥ to bedding	⑬ ⑭	"	"	Indirect	0.30	134	2239 m/sec	✓
⊥ to bedding	⑭ ⑮	"	"	Indirect	0.30	129	2326 m/sec	✓
// to bedding	④ ⑤	"	"	Indirect	0.52	258	2016 m/sec	✓
// to bedding	③ ⑤	"	"	Indirect	0.58	245	2367 m/sec	✓
// to bed	⑥ ⑦	"	"	Indirect	0.53	239	2218 m/sec	✓
// to bed	④ ⑧	"	"	Indirect	0.59	220-302	1864 m/sec	✓
// to bed	③ ⑬	"	"	Indirect	0.30	105	2857 m/sec	✓
// to bed	③ ⑭	"	"	Indirect	0.85	448	1897 m/sec	✓
// to bed	③ ⑯	"	"	Indirect	0.15	47	3191 m/sec	✓
⊥ to bed	③ ⑬	"	"	Indirect	0.44	184	2311 m/sec	✓
⊥ to bed	③ ⑭	"	"	"	0.715	303	2360 m/sec	✓
// to bed	③ ②	"	"	"	0.46	588	1633 m/sec	✓

① Orientation of direct line between transmitter/receiver, w.r.t. bedding

② Test point numbers (ie, receiver & transmitter locations & numbers)

③ Weathered, fresh & rough, fresh & ground flat, etc

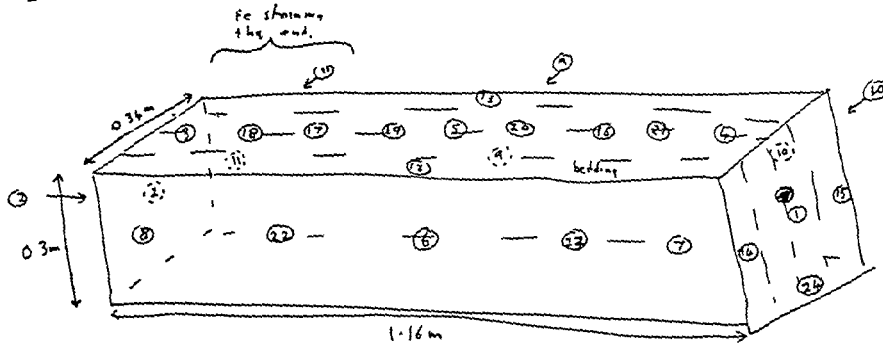
④ Direct, Semi-direct, indirect.

⑤ Separation of transducer heads (ie, test points) in a straight line

⑥ Specimen no's, location of each spec w.r.t. Test points

Block 6

bedding discernable, although stone nearly massive



Roughness 1

PUNDIT TEST

Page ① of ②

Date :- 23/8/85

Test Locality :- Durnis Workshop

Test location (with locality) :- Blocks 7 (Nunama Nunamara sst)

General condition of test surface/rock body :- Fresh, fully sawn block (all surfaces flat & straight)

Test orientation^① :- See diagram

Comments, Fractures, etc: none

	Test between and		Transducer head size	Condition of Test points	Test method	(surface) Path length (L) metres	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$	
// bedding	①	②	large	Fresh, sawn flat	Direct	1.134	473	2397 m/sec	✓
L bedding	③	④	"	"	Direct	0.34	144	2361 m/sec	✓
L bedding	⑤	⑥	"	"	Direct	0.34	146	2329 m/sec	✓
L bedding	⑦	⑧	"	"	Direct	0.34	137	2482 m/sec	✓
diag to bed	⑨	⑨	"	"	Semi-direct	0.23	83	2771 m/sec	✓ - slightly h. due to F _o si
diag to bed	⑩	⑩	"	"	Semi-direct	0.225	85	2647 m/sec	✓
diag to bed	⑪	⑪	"	"	Semi-direct	0.23	95	2421 m/sec	✓
diag to bed	⑫	⑫	"	"	Semi-direct	0.22	90	2444 m/sec	✓
diag to bed	⑬	⑬	"	"	Semi-direct	0.23	91	2527 m/sec	✓
diag to bed	⑭	⑭	"	"	Semi-direct	0.22	91	2418 m/sec	✓
// bedding	①	⑩	"	"	Semi-direct	1.055	54.7	1929 m/sec	✓ - due to F _o
// bedding	①	⑪	"	"	Semi-direct	0.86	371	2318 m/sec	✓
// bedding	①	⑫	"	"	Semi-direct	0.60	259	2317 m/sec	✓
// bedding	①	⑮	"	"	Semi-direct	0.45	191	2356 m/sec	✓
// bedding	①	⑯	"	"	Semi-direct	0.31	132	2348 m/sec	✓
diag to bed	⑮	⑮	"	"	Semi-direct	1.075	459	2342 m/sec	✓
diag to bed	⑮	⑮	"	"	Semi-direct	0.865	354	2444 m/sec	✓
diag to bed	⑮	⑮	"	"	Semi-direct	0.64	256	2500 m/sec	✓
diag to bed	⑮	⑮	"	"	Semi-direct	0.48	190	2526 m/sec	✓
diag to bed	⑮	⑮	"	"	Semi-direct	0.36	141	2553 m/sec	✓

- ① Orientation of direct line between transmitter/receiver, WRT. bedding
 ② Test point numbers (ie, receiver & transmitter locations & numbers)
 ③ Weathered, fresh & rough, fresh & ground flat, etc
 ④ Direct, Semi-direct, indirect.

- ⑤ Separation of transducer heads (ie, test points) in a straight line
 ⑥ Specimen no's, location of each spec WRT. Test points

PUNDIT TEST

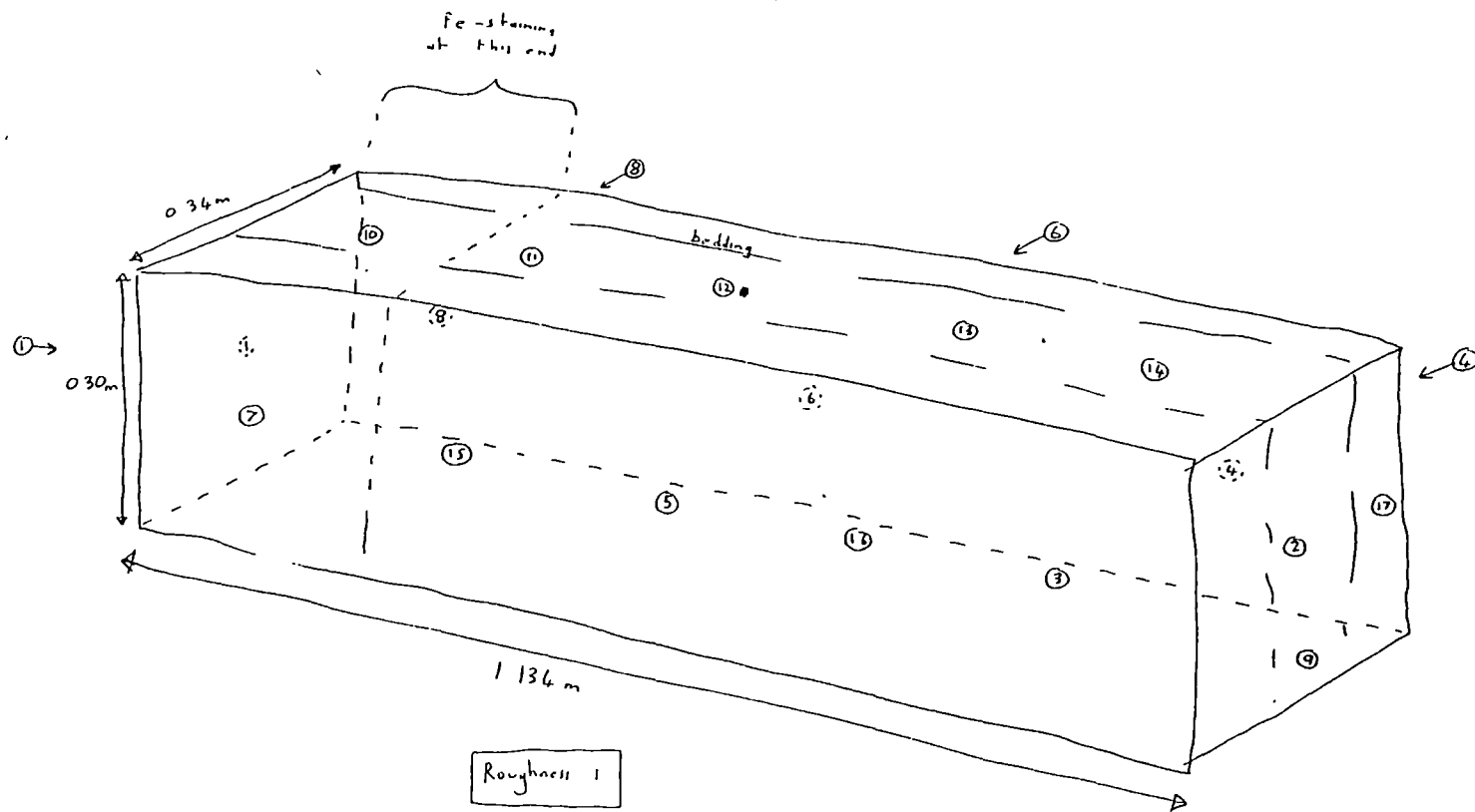
Date:-
 Test Locality:-
 Test location (withm locality):- Block 7 (Nunamun
 General condition of test surface/rock body:-
 Test orientation:-
 Comments, Fractures, etc:-

Test between and	⑩	Large	Fresh, same flat	Indirect	0.86	4.70	1830	m/sec	✓
Transducer head size	⑪	"	"	Indirect	0.65	309	2104	"	✓
Condition of test points	⑫	"	"	Indirect	0.38	160	2375	"	✓
	⑬	"	"	Indirect	0.20	81	2469	"	✓
	⑭	"	"	Indirect	0.85	582	1460	"	✓
	⑮	"	"	Indirect	0.65	317	2050	"	✓
	⑯	"	"	Indirect	0.39	176	2316	"	✓
	⑰	"	"	Indirect	0.20	85	2353	"	✓

- ① Orientation of direct line between transmitter/receiver, W.K.T. bedding
- ② Test point numbers (in, receiver & transmitter locations & numbers)
- ③ Weathered, fresh & rough, fresh & ground flat, etc.
- ④ Direct, semi-direct, indirect.
- ⑤ Separation of transducer heads (ie, test points) in a straight line
- ⑥ Specimen no.s, location of each spec W.K.T. Test points

Block 7

Bedding faint but discernable (nearly massive)



PUNDIT TEST

Date :- 5/9/85

Test Locality :- Dunes Yard

Test location (within locality) :- Block 8 (Nunamra ss

General condition of test surface/rock body :- fresh, sawn flat surfaces

Test orientation^① :-

Path length measured between transducer centres or (Path length between nearest edges of transducer

Comments, Fractures, etc: no Fractures, block looks homogeneous

Test between and ^②		Transducer head size	Condition of Test points ^③	Test method ^④	Path length (L) metres ^⑤	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$ (m/sec)	
// bedding	①	②	large	fresh, sawn flat	Indirect	0.1 (0.05)	37	2703 (1351)
"	①	③	"	"	"	0.2 (0.15)	125	1600 (1200)
"	①	④	"	"	"	0.3 (0.25)	177	1695 (11612)
"	①	⑤	"	"	"	0.4 (0.35)	274	1460 (1277)
"	①	⑥	"	"	"	0.5 (0.45)	431	1160 (1044)
"	①	⑦	"	"	"	0.6 (0.55)	442	1357 (1246)
"	①	⑧	"	"	"	0.7 (0.65)	602	1163 (1080)
"	①	⑨	"	"	"	0.8 (0.75)	695	1151 (1079)
"	①	⑩	"	"	"	0.9 (0.85)	847	1063 (1004)
"	①	⑪	"	"	"	1.0 (0.95)		Reading diff. would give
"	①	⑫	"	"	"	1.1		Reading would give
"	⑬	⑭	"	"	Direct	1.35	316	4272 (!!!)
"	⑮	⑯	"	"	Direct	1.35	584	2312
"	⑰	⑱	"	"	Direct	1.35	833	1621
"	⑲	⑳	"	"	Direct	1.35	740	1824
⊥ bedding	㉑	㉒	"	"	Direct	0.22	95	2316
⊥ bed.	㉓	㉔	"	"	Direct	0.22	91	2418
⊥ bed	㉕	㉖	"	"	Direct	0.22	89	2471

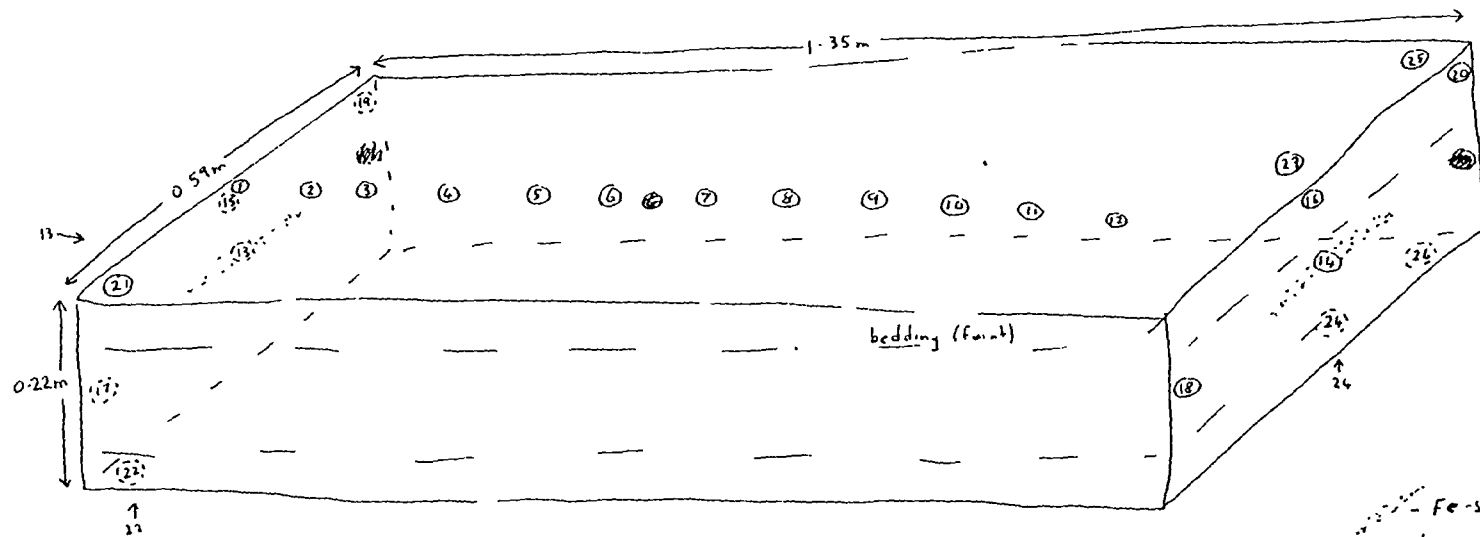
- ① Orientation of direct line between transmitter/receiver, w.r.t. bedding
 ② Test point numbers (ie, receiver & transmitter locations & numbers)
 ③ Weathered, fresh & rough, fresh & ground flat, etc.
 ④ Direct, semi-direct, indirect.

- ⑤ Separation of transducer heads (ie, test points) in a straight line
 ⑥ Specimen no.'s, location of each spec w.r.t. Test points

Block 8 - Nunamara sst

Bedding faint - virtually massive

All Roughness ①



Fe-stain
(continuous layer
13 → 14??)

PUNDIT TEST

Date :- 5/9/85

Test Locality :- Duni Yard

Test location (with locality) :- Block 9 (Nunamara)

General condition of test surface/rock body :- Rough Quarried block, test spots ground flat (& fresh surfaced)

Test orientation^① :-

Path length :- between transducer centres

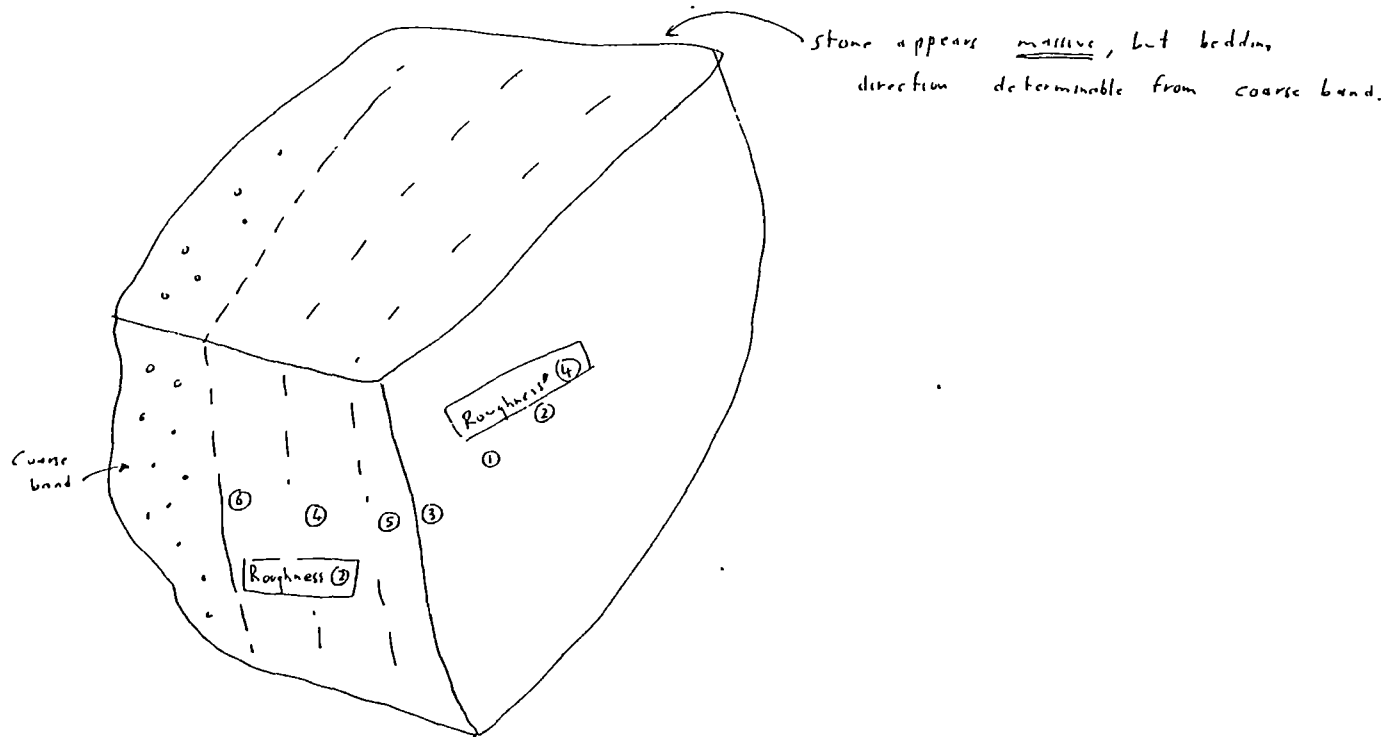
Comments, Fractures, etc: none in tested part

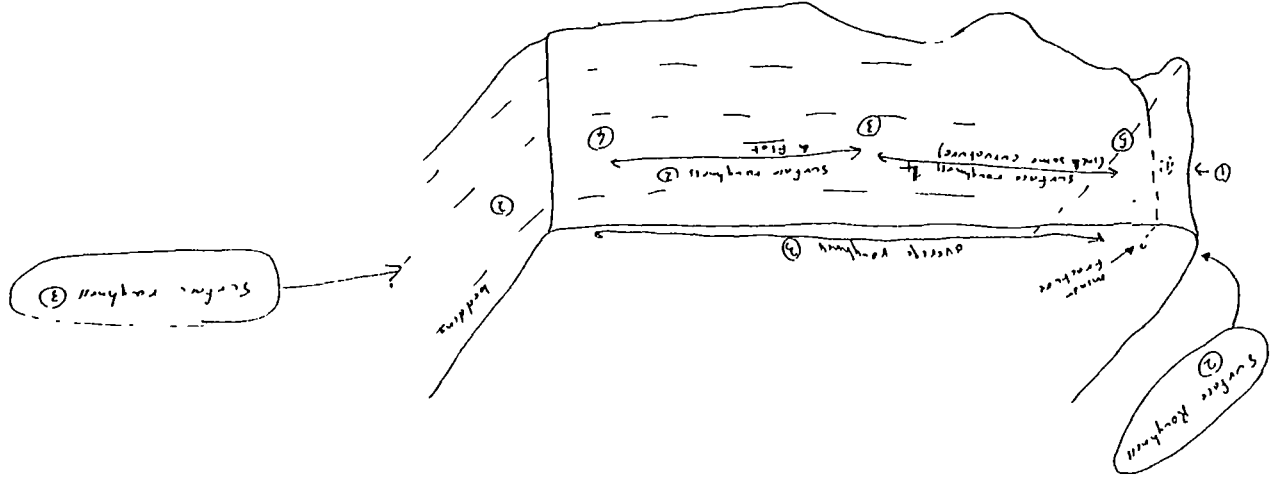
	Test between and ②		Transducer head size	Condition of Test points ③	Test method ④	Path length (L) metres ⑤	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$	
// bed	①	②	large	Fresh, ground flat	Indirect	0.29	354	819 m/sec	
"	①	③	"	"	"	0.32	4.07	786 m/sec	
"	②	③	"	"	"	0.60			could not get reading.
⊥ bed	④	⑤	"	"	"	0.33	252	1310 m/sec	
⊥ bed	④	⑥	"	"	"	0.34	240	1417 m/sec	
⊥ bed	⑤	⑥	"	"	"	0.67	536	1250 m/sec	
diag. bed	①	④	"	"	Semi-direct	0.5	540	926 m/sec	reading correct but hard to get.
diag. bed	②	⑥	"	"	"	0.87			could not get reading
diag. bed	④	②	"	"	"	0.7			could not get reading
diag. bed	①	⑥	"	"	"	0.8			could not get reading
ng (nearly ⊥ bed)	③	④	"	"	"	0.36	315	1143 m/sec	

- ① Orientation of direct line between transmitter/receiver, w.r.t. bedding
 ② Test point numbers (ie, receiver & transmitter locations & numbers)
 ③ Weathered, fresh & rough, fresh & ground flat, etc.
 ④ Direct, Semi-direct, indirect

- ⑤ Separation of transducer heads (ie, test points) in a straight line
 ⑥ Specimen no's, location of each spec w.r.t. Test points

Block 9 - Nunamara sst





Bedding fairly obvious

PUNDIT TEST

Date :- 6/4/85 Test Locality :- Durns Yard Test location (within locality) :- Block 10 (Number of transducer heads

General condition of test surface/rock body :- Rough quarried block, test spots ground flat

Test orientation :-

Comments, Fractures, etc : One fracture on surface, depth uncertain (see diag)

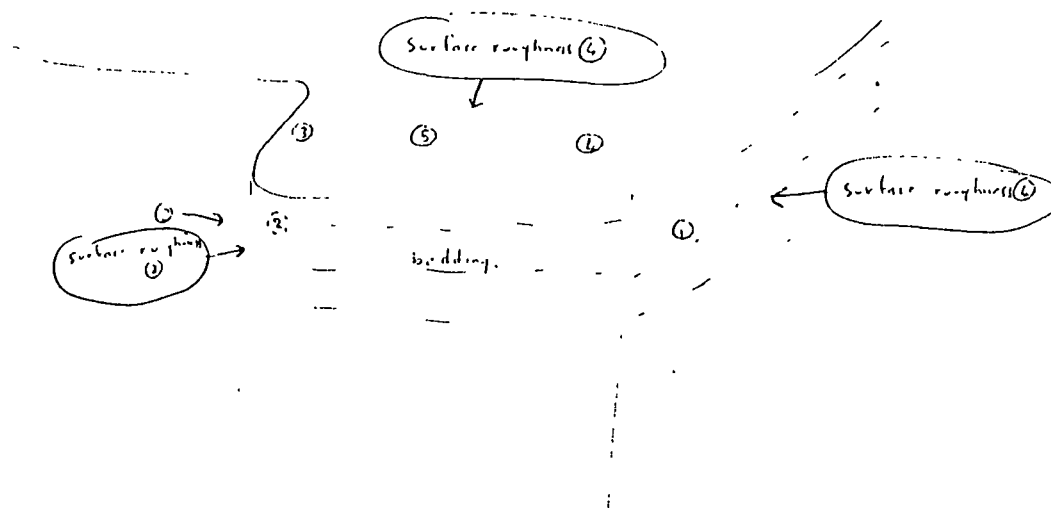
Path lengths measured between centre of transducer heads

Test between ③ and	①	③	④	⑤	⑥	⑦
Transducer head size	Large	Large	Large	Large	Large	Large
Condition of ③ Test points	Fract, ground flat	Fract, ground flat	Fract, ground flat	Fract, ground flat	Fract, ground flat	Fract, ground flat
Test ④ method	Direct	Indirect	Indirect	Indirect	Indirect	Indirect
Path length ⑤ (L) metres	1.05m	0.36m	0.51	0.88	0.79	0.50
Transit time (T) / sec	74.2	208	360	618	525	380
Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$	1415 m/sec	1731 m/sec	1417 m/sec	1424 m/sec	1505 "	1316 "

bulky

- ① Orientation of direct line between transmitter/receiver, WRT. bedding
- ② Test point numbers (ie, receiver & transmitter locations & numbers)
- ③ Weathered, fresh & rough, fresh & ground flat, etc
- ④ Direct son - direct indirect
- ⑤ Separation of transducer heads (ie, test points) in a straight line
- ⑥ Specimen nos, location of each spec. WRT. Test points

Block 11 - N. Atlantic SST



PUNDIT TEST

Date :- 6/4/85

Test Locality:- During Yr.d

Test location (within locality):- Block II (Nanamare st')

General condition of test surface/rock body:- fresh, rough, greenish black, test spots
greenish black

Test orientation^①:-

Path lengths measured betw.
boundary centers.

Comments, Fractures, etc: none

[illegible]

- ① Orientation of direct line between transmitter/receiver, w.R.T. bedding
- ② Test point numbers (i.e. receiver & transmitter locations & numbers)
- ③ Weathered, fresh & rough, fresh & ground flat, etc
- ④ Direct semi-direct indirect

- ⑤ Separation of transducer heads (ie, test points) in a straight line
⑥ Specimen no.'s, location of each spec w.r.t Test points

PUNDIT TEST

Page 6

Date :- 6/4/85

Test Locality :- Durin's Yard

Test location (with locality) :- Block 12 (Numerous
(usually lower quality, still, & strong building)

General condition of test surface/rock body :- fresh, sawn slab surface (edges still rough, but only
sawn surfaces tested)

Test orientation^① :-

distances measured between transducers to
* (between nearest edges of transducers)

Comments, Fractures, etc: See diag.

	Test between and ②		Transducer head size	Condition of Test points ③	Test method ④	Path length (L) metres ⑤	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$		
//bed	1	2	Large	fresh, sawn flat	Indirect	0.1 (0.05)*	37	2703	(1351)	*
"	1	3	"	"	"	0.2 (0.15)	106	1837	(1415)	
"	1	4	"	"	"	0.3 (0.25)	155	1935	(1613)	
"	1	5	"	"	"	0.4 (0.35)	205	1951	(1707)	
"	1	6	"	"	"	0.5 (0.45)	343	1458	(1312)	
"	1	7	"	"	"	0.6 (0.55)	432	1389	(1273)	
"	1	8	"	"	"	0.7 (0.65)	522	1341	(1245)	
"	1	9	"	"	"	0.8	576	1183		
"	1	10	"	"	"	0.9	764	1178		
"	1	11	"	"	"	1.0	814	1185		
"	1	12	"	"	"	1.1	929	1184		
"	1	13	"	"	"	1.2	1014	1183		
"	1	14	"	"	"	1.3	1096	1186		
"	1	15	"	"	"	1.4	1178	1188		
"	1	16	"	"	"	1.5	1263	1188		
"	1	17	"	"	"	1.6				can't get reading
"	②	②	"	"	Direct	0.34	127	2677		

- ① Orientation of direct line between transmitter/receiver, w.r.t. bedding
- ② Test point numbers (ie, receiver & transmitter locations & numbers)
- ③ Weathered, fresh & rough, fresh & ground flat, etc.
- ④ Direct semi-direct indirect

- ⑤ Separation of transducer heads (ie, test points) in a straight line
- ⑥ Specimen no's, location of each spec w.r.t. Test points

PUNDIT TEST

Date :-

Test Locality :-

Test location (within locality) :- Block 12

General condition of test surface/rock body :-

Test orientation^① :-

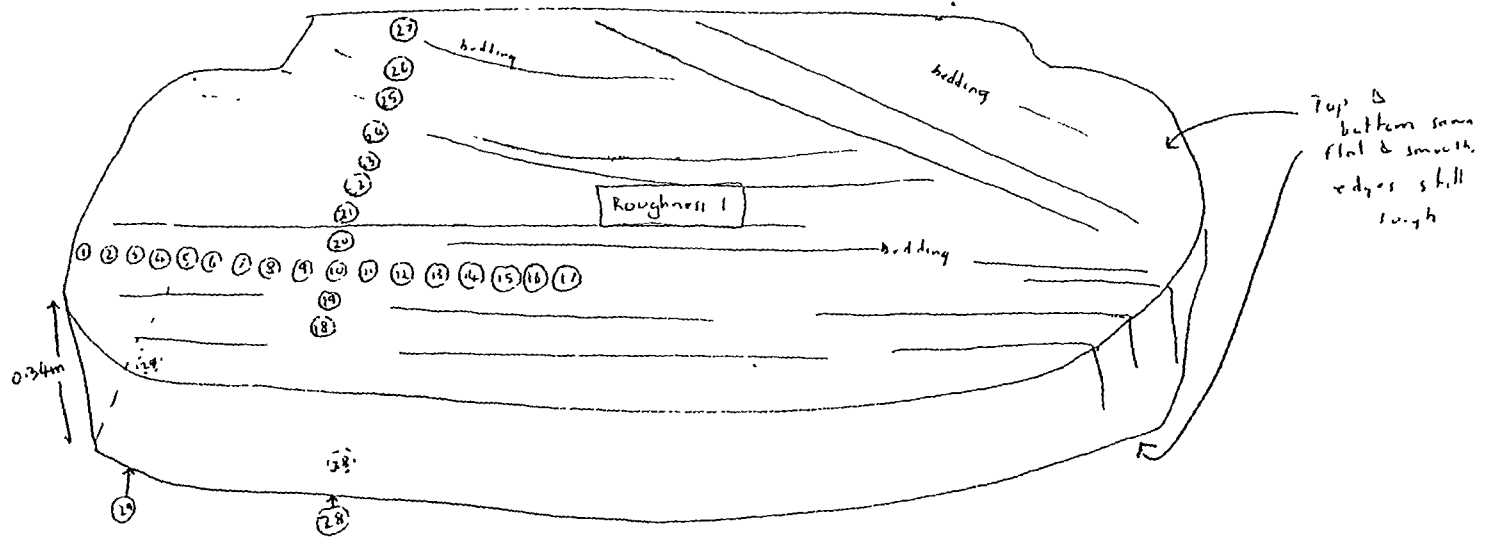
Comments, Fractures, etc.:

	Test between ^② and		Transducer head size	Condition of ^③ Test points	Test method ^④	Path length ^⑤ (L) metres	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$	
⊥ bed	(13)	(14)	Large	fresh, sawn flat	Indirect	0.1	30	3333	edge of block
"	(13)	(15)	"	"	"	0.2	69	2899	
"	(13)	(16)	"	"	"	0.3	118	2542	
"	(13)	(21)	"	"	"	0.4	187	2139	
"	(13)	(23)	"	"	"	0.5	342	1462	
"	(13)	(23)	"	"	"	0.6	407	1474	
"	(13)	(24)	"	"	"	0.7	557	1257	
"	(13)	(25)	"	"	"	0.8	635	1260	
"	(13)	(26)	"	"	"	0.9	718	1253	
"	(13)	(27)	"	"	"	1.0	789	1267	
// bed	(18)	(28)	"	# "	Direct	0.34	143	2378	

- ① Orientation of direct line between transmitter/receiver, w.r.t. bedding
 ② Test point numbers (ie, receiver & transmitter locations & numbers)
 ③ Weathered, fresh & rough, fresh & ground flats, etc.
 ④ Direct, Semi-direct, indirect.

- ⑤ Separation of transducer heads (ie, test points) in a straight line
 ⑥ Specimen no's, location of each spec w.r.t. Test points

Block 12 - Numerical SST
Bedding Pronounced



PUNDIT TEST

Date:- 6/1/85

Test Locality:- D.ing Yard

Test location (with locality):- Block 13 (Nunimara, ss)

General condition of test surface/rock body:- Fresh sawn, bluish (2 sides flat same, edges rough).

Test orientation:-

Path length measured between transducer head centers.

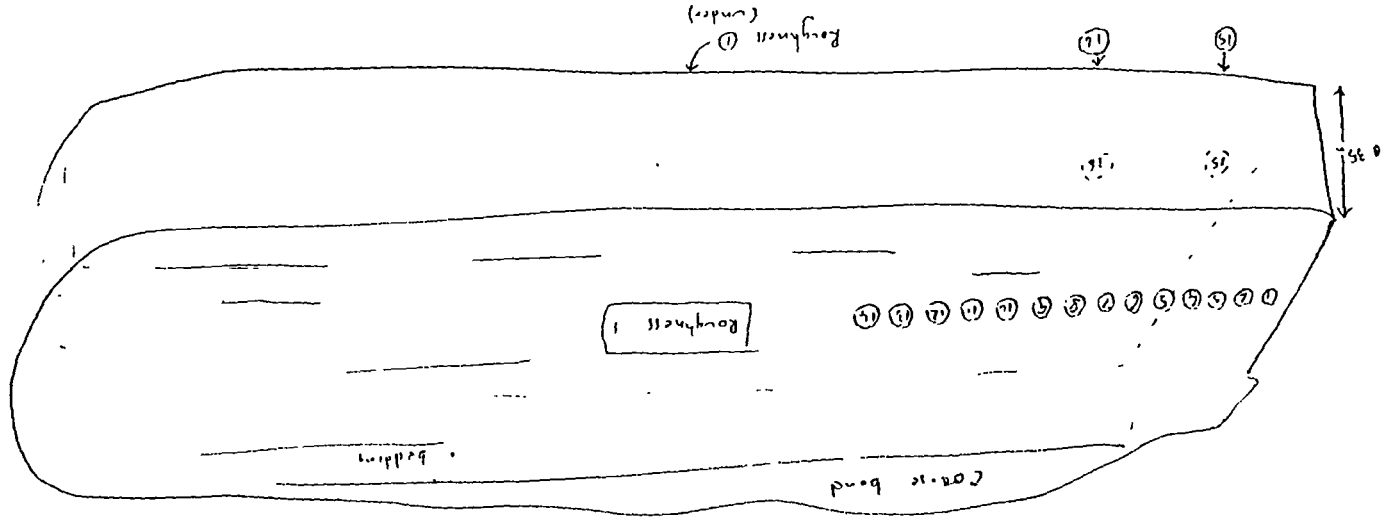
Comments, Fractures, etc:- none.

Test between and		Transducer head size	Condition of Test points	Test method	Path length (L) metres	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$	
bed.	①	②	Large	fresh sawn flat	Indirect	0.1	32	3125
"	1	3	"	"	"	0.2	77	2547
"	1	4	"	"	"	0.3	142	2113
"	1	5	"	"	"	0.4	253	1581
"	1	6	"	"	"	0.5	326	1534
"	1	7	"	"	"	0.6	400	1500
"	1	8	"	"	"	0.7	537	1304
"	1	9	"	"	"	0.8	618	1244
"	1	10	"	"	"	0.9	697	1241
"	1	11	"	"	"	1.0	775	1240
"	1	12	"	"	"	1.1	856	1285
"	1	13	"	"	"	1.2	935	1283
"	1	14	"	"	"	1.3		cant get reading.
bed	②	⑬	"	"	Direct	0.35	139	2518
"	⑦	⑭	"	"	Direct	0.35	130	2692

- ① Orientation of direct line between transmitter/receiver, w.r.t bedding
 ② Test point numbers (ie, receiver & transmitter locations & numbers)
 ③ Weathered, fresh & rough, fresh & ground flat, etc
 ④ Direct see - direct indirect

- ⑤ Separation of transducer heads (ie, test points) in a straight line
 ⑥ Specimen no's, location of each spec w.r.t. Test points

Block 13
 Nundama 55°
 N. 20.4° E. 11.1° S.



PUNDIT TEST

Date: 28 May 1985 Test Locality: Ten-tree Quarry

Test location (within locality): block on quarry floor

General condition of test surface/rock body: Fresh stone

Test orientation^①: Parallel to bedding

Comments, Fractures, etc.: Bedding parting visible at test point ④

Test between and ^②		Transducer head size	Condition of ^③ Test points	Test method ^④	Path length (L) metres ^⑤	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$	
①	②	Small	Fresh & ground Flat	Direct	0.81	4980	0.0016265 m/ μ sec	
①	②	Big	"	"	0.81	5160	0.001570 m/ μ sec	
							$\bar{V} = 0.0016285 \text{ m}/\mu\text{sec}$	
							$= 1626.5 \text{ m/sec}$	

- ① Orientation of direct line between transmitter/receiver, w.r.t. bedding
 ② Test point numbers (i.e., receiver & transmitter locations & numbers)
 ③ Weathered, fresh & rough, fresh & ground Flat, etc.
 ④ Direct, semi-direct, indirect.

- ⑤ Separation of transducer heads (i.e., test points) in a straight line
 ⑥ Specimen no's, location of each spec w.r.t. Test points

PUNDIT TESI

Date :- 28 May 1985 Test Locality :- Ped-trees Quarry

Test location (within locality) - block on quarry floor

General condition of test surface/rock body:- Fresh stone

Test orientation ①:- parallel to bedding

Comments, Fractures, etc:

Test between and	Transducer head size	Condition of Test points	Test method	Path length (L) metres	Transit time (T) μ sec	Ultrasonic pulse velocity (V) $V = \frac{L}{T}$
③	④	Big	Direct	0.68	402.0	0.0016915 m/ μ sec
③	④	Small	" " "	0.68	202.0	0.0033663 m/ μ sec
						measurement in big head:- 1691.5 m/sec

- ① Orientation of direct line between transmitter/receiver, WRT bedding
- ② Test point numbers (i.e. receiver & transmitter locations & numbers)
- ③ Weathered, fresh & rough, fresh & ground flint, etc.
- ④ Direct, semi-direct, indirect.

- ⑤ Separation of transducer heads (ie, test points) in a straight line
⑥ Specimen no's, location of each spec w.r.t. Test points

PUNDIT TEST

Date :- 6/6/85

Test Locality :- Tea-tree Quarry

Test location (within locality) :- main face

General condition of test surface/rock body :- weathered surface, prob still a little case hardened. Fresh spall ground flat.

Test orientation ^① :- parallel to bedding

Comments, Fractures, etc :- none between test points.

Test between and ^②		Transducer head size	Condition of Test points ^③	Test method ^④	Path length (L) metres ^⑤	Transit time (T) μ sec	Ultrasonic Pulse velocity (V) $V = \frac{L}{T}$
⑤	⑥	Small	Ground flat, but poss a little case hardened	Indirect	0.65	323.0	2012 m/sec
⑤	⑥	Large	"	Indirect	0.65	327.0	1988 m/sec
							$\Delta V = \underline{2000 \text{ m/sec}}$

- ① Orientation of direct line between transmitter/receiver, WRT. bedding
 ② Test point numbers (ie, receiver & transmitter locations & numbers)
 ③ Weathered, fresh & rough, fresh & ground flat, etc
 ④ Direct, semi-direct, indirect.

- ⑤ Separation of transducer heads (ie, test points) in a straight line
 ⑥ Specimen no's, location of each spec WRT Test points

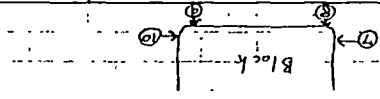
PUNDIT TEST

Date :- 6/6/85

Test Locality :- Tareer Quarry

Test location (with locality) :- Fresh block on floor of Quarry

Experiment - testing Direct & indirect methods on same block. Layout of test points (viewed from above block) :-



General condition of test surface/rock body :- Fresh shun, ground flat

Test orientation :- parallel to bedding

Comments, Fractures, etc :

Test between ⑦ and ⑧	⑩	⑨	⑧	⑦
Transducer head size	Small	Small	"	"
Condition of test points	fresh, ground flat	"	"	"
Test method	Direct	Indirect	"	"
Path length (L) metres	0.51	0.42	253.0	177.0
Transit time (T) / sec				
Ultrasonic Pulse velocity (V)	2881 m/sec	1660 m/sec		

- ① Orientation of direct line between transmitter/receiver, WRT. bedding
- ② Test point numbers (i.e. receiver & transmitter locations & numbers)
- ③ Weathered, fresh & rough, fresh & ground flat, etc
- ④ Direct, Semi-direct, indirect
- ⑤ Separation of transducer heads (i.e. test points) in a straight line
- ⑥ Specimen no's, location of each spec. WRT. Test points

APPENDIX SEVEN**THE DURABILITY OF SANDSTONES WHEN SUBJECTED TO THE
CYCLIC SALT CRYSTALLISATION TEST**

This appendix is a copy of pages 210 - 222 of Sharples *et al.* (1984), and is referred to in Chapter Six of this thesis.

SECTION (B:5.3) THE DURABILITY OF SANDSTONES WHEN SUBJECTED TO
THE CYCLIC SALT CRYSTALLISATION TEST

(B:5.3.1) Nature and purpose of the test

As mentioned in Section (B:4.2), the purpose of conducting the cyclic salt crystallisation test is to artificially induce decay processes in sandstone samples for the purpose of obtaining a measure of the actual durability of the stone when exposed to a stressful environment. Although the conditions created are much more stressful than would ever be experienced in an actual building environment, and the sandstone decay consequently more rapid, the test should give an accurate indication of which stones are more or less durable than others. To an extent, this is the case, although one important point which will be discussed later is that this test only applies to specific types of stress to the stone, and the stones tested could well have quite different durabilities relative to each other if subjected to a different type of stress in the building environment.

For the purposes of this type of test, many workers have used a sodium sulphate crystallisation test (e.g. see Spry 1983). However, based on a recommendation from Mr Peter Spratt, the present testing was performed using ordinary NaCl salt. This provides a test which is very aggressive, and uses the same salt which most commonly attacks stone in the Tasmanian building environment.

The testing procedure is outlined in the appendices. Briefly, the procedure involves alternate soaking of samples in NaCl solution and drying them, in conjunction with alternate heating and near-freezing cycles. This provides wet/dry, hot/cold cycles in the presence of salt which imitate, with exaggeration, the cycles found in the Tasmanian building environment.

(B:5.3.2) Quantification of Durability in Cyclic Salt Test

The durability of sandstones when subjected to the cyclic salt crystallisation test can be recording in several ways, as follows:

Non-quantitative:

1. Subjective description of changes with each cycle.
2. Photograph and describe condition of blocks after standard number of cycles completed, using untested block specimens as control specimens for comparison.

Quantitative:

211.

3. Note cycle number at which first signs of damage become apparent.
4. Measure volume % loss of the specimen. This is done by measuring the volume of the specimen prior to testing, and then measuring the volume of the specimen after a standard number of cycles to determine volume lost. Volume is measured by displacement of water in a beaker. Uptake of water by the stone has no effect on the measurement within the time scale and accuracy of the technique.
5. Measure weight % loss of the specimen. This is more difficult to do, and has not been undertaken in the present project. The difficulty is that uptake of water and salt by the specimen would offset weight loss due to decay, to a degree would could not easily be determined.

The only way to carry out weight % loss measurements would be to carry out the test in such a way that material lost from the specimen was collected and weighed separately.

For the purposes of analysis and application, the data obtained from the salt crystallisation test needs to be presented as a single numerical value. Consideration was given during this work to combining the two quantitative parameters obtained, cycle number at which damage first appears (F), and volume % loss on the 10th cycle (V), into a single numerical value. This value could be obtained from one of the functions (FV), (F/V) or (V/F). However, it was considered that it was not necessarily meaningful or valid to combine these two values. For instance, if two specimens begin decaying after different numbers of cycles, but have lost similar volume percentages by the tenth cycle, can we be sure that their durabilities differ in the ways which any of the aforementioned functions would indicate? One of the specimens would have resisted decay longer, but then have started breaking down faster than the other. Which specimen, then, is the most durable? It is clear that a simple answer cannot be given - such data would tend to indicate that the relative durability of the specimens in actual building usage would depend largely on the purpose and environment in which they were put to use. However, any of the above three functions would misleadingly give us numerical results implying that one was simply "more durable" than the other.

Because of complexities of this sort, this study uses the simple value of volume % loss on the tenth cycle as the most appropriate available means of quantifying durability. Thus, for the purposes of this study:

V = Volume % loss from specimen on 10th cycle

212.

where V = a function of durability when subjected to cyclic salt crystallisation test

This gives values ranging from $V = 0\%$ loss for maximum durability, and $V = 100\%$ loss for minimum durability.

The cycle at which damage first appears (F) constitutes a secondary, measure of durability, on which less emphasis is placed in this study since:

- (a) Its measurement is slightly subjective, unlike the measurement of (V), and
- (b) since specimens of obviously widely varying durabilities (as determined by measurement of (v)) may have similar values of F , it does not appear that F discriminates very well between sandstones of differing durabilities.

(B:5.3.3) Results and Analysis of Results

Quantitative results of the cyclic salt crystallisation tests are presented in the accompanying Table (B:5.3.1). The test was carried out on 40 samples, but only 34 could be used in the following analysis due to incomplete data on the other measured properties of 6 samples.

Since the cyclic salt crystallisation test gives a direct measure of actual stone durability, this gives us an opportunity to attempt to correlate that durability with measured stone properties in order to determine to exactly what extent the various measured properties do influence durability.

On the grounds explained in Section B:3.3, it can initially be assumed that effective porosity (P) detrimental clay-content (C) and dry point load strength index (S) are the measured stone properties having the major influence on Tasmanian sandstone durability, and these properties are also tabulated for the 34 samples on table (B:5.3.1).

As a first step, the three properties of each sample, P , C , and S were plotted separately against their durabilities in the salt test (expressed as the percentage volume lost after 10 cycles). If the durabilities were primarily related to just one of these three properties, that property would plot in a neat linear relationship to the durability. By performing regression analysis we can determine the degree to which the actual scatter of data points approaches a linear relationship. In this way we obtain a "regression line" which best fits the scatter of data points, and a

Table (B.5.3.1) Cyclic Salt Crystallisation Test Results

Source	Field No.	Vol. % lost on 10th cycle (V)	Cycle at which 1st loss noted (F)	Effective Porosity Vol. % (P)	Detrimental Clay Content (Smectite ± Vermiculite) Vol. % (C)	Dry Point Load Strength Index (MPa) (S)	S/P	S/C	$\frac{1}{F + C}$	$\frac{S}{F + C}$
(Etna) coloured Quarry	Etna 1	25	2	10.76	1.44	1.18	0.11	0.82	0.082	0.097
Pontville	Etna 2	100	2	13.01	1.1	0.26	0.02	0.24	0.071	0.018
(Etna) white Quarry, Pontville	Etna 3	14	2	12.06	0.0	0.8	0.07	00	0.083	0.066
Lachlan	Lach 1	10	3	9.7	0.0	0.98	0.1	00	0.103	0.101
Melton Mowbray	MM1	16	5	14.61	5.0	1.51	0.1	0.3	0.051	0.077
Cobbs Hill	Cobb 1	37	5	12.84	1.5	0.64	0.05	0.43	0.07	0.045
Linden	L1	3	5	9.11	4.2	1.82	0.20	0.43	0.075	0.137
	L2	<5	3	11.83	3.25	1.11	0.09	0.34	0.066	0.074
(Rizzolo) Oatlands	Riz 1	6	2	16.35	10.32	0.9	0.06	0.09	0.037	0.034
Nunamara	N1	3	10	10.66	1.25	1.19	0.11	0.95	0.084	0.10
Braemar	B1	10	2	13.04	3.06	0.40	0.03	0.13	0.062	0.025
Connorville	Con 1	5	5	9.07	0.0	1.75	0.19	00	0.110	0.193
Copping	Cop 2	6	7	8.81	0.0	0.71	0.08	00	0.114	0.081
Molesworth	FB 1	7	8	8.97	0.0	2.11	0.24	00	0.111	0.235
Campania	Cam 1	14	4	12.8	3.42	0.31	0.02	0.09	0.062	0.019
Ouse (Quartz Arenite)	O1	3	5	15.3	1.46	0.76	0.05	0.52	0.06	0.045
Orehampton	Oak 1	100	3	13.58	0.0	0.10	0.01	00	0.074	0.007
	Oak 2	8	3	13.28	0.0	1.67	0.13	00	0.075	0.126
Mike Howes Marsh	MH 1	4	2	10.15	0.0	2.46	0.24	00	0.099	0.242
New South Wales (Wendabyne)	NSW 1	6	4	10.37	0.0	1.04	0.10	00	0.096	0.100
Ross	Ross 1	23	4	15.86	0.0	0.34	0.02	00	0.063	0.021
	Ross 3	12	2	15.89	0.0	0.43	0.03	00	0.063	0.027
	Ross 6	7	5	13.95	0.0	0.68	0.05	00	0.072	0.049
Port Arthur Quarries	PA 1	100	1	17.25	21.44	0.25	0.01	0.01	0.026	0.006
	PA4	4	7	10.11	12.0	1.99	0.20	0.17	0.045	0.09
	PA5	5	2	12.39	0.0	0.31	0.03	00	0.081	0.025
Knocklofty	K1	<5	7	10.42	10.26	2.42	0.23	0.24	0.048	0.117
	K2	11	7	10.27	7.4	0.78	0.08	0.11	0.057	0.044
Teatree	TT5	0	<10	10.36	2.0	1.02	0.1	0.51	0.081	0.083
	LP03	3	5	10.4	4.59	1.56	0.15	0.34	0.067	0.104
Trinity Church	Tr 2	3	?	17.11	9.6	0.83	0.05	0.09	0.037	0.031
Ventenat Point	V1	3	2	10.47	0.0	1.29	0.12	00	0.096	0.123
	V2	8	9	11.7	7.48	0.47	0.04	0.06	0.052	0.025
Waterworks	WW1	13	4	12.82	0.0	0.91	0.07	00	0.078	0.071

213.

"correlation co-efficient" r , from which we can obtain the figure $100r^2$ which is the degree to which variation in one of the parameters plotted correlates with variation in the other parameter plotted. That is, $100r^2$ is a measure of the degree to which the parameters plotted against each other have a linear relationship with one another. Thus, $100r^2 = 100\%$ would mean the relationship was completely linear, and $100r^2 = 0\%$ would mean there was no relationship whatsoever.

The accompanying figure, Fig. (B:5.3.1 a, b, c) shows each of the three properties S, P and C plotted graphically against durability in the salt test, and Table (B:5.3.2) below tabulates the regression line equation and $100r^2$ for each of these relationships.

Relationship	Regression Line Equation	$100r^2$
LINEAR REGRESSIONS - INDIVIDUAL PROPERTIES <u>VS</u> DURABILITIES		
C vs V	$C = 131.38 - 7.55 V$	5.247%
P vs V	$P = 11.706 + 0.03 V$	12.95%
S vs V	$S = 1.217 - 0.011 V$	22.85%
LOGARITHMIC REGRESSIONS - COMBINED PROPERTIES <u>VS</u> DURABILITIES		
S/C vs V	$(S/C) = 10^{(-0.3-0.005V)}$	8.25%
S/P vs V	$(S/P) = 10^{(-1.011-0.009V)}$	45.0%
1/P+C vs V	$(1/P+C) = 10^{(-1.147-0.001V)}$	0.0004%
S/P+C vs V	$(S/P+C) = 10^{(-1.082-0.01V)}$	45.6%
LINEAR REGRESSION - COMBINED PROPERTIES <u>VS</u> DURABILITIES		
S/P+C vs V	$(S/P+C) = 0.095-0.001V$	15.46%

TABLE (B:5.3.2)

Degrees of correlation obtained between durability in the salt test and various combinations of properties of 34 specimens.

Note: C = Detrimental Clay Content, Vol. %
P = Effective Porosity, Vol. %
S = Dry Point Load Strength Index, MPa
V = Vol. % loss after 10 salt test cycles.

214.

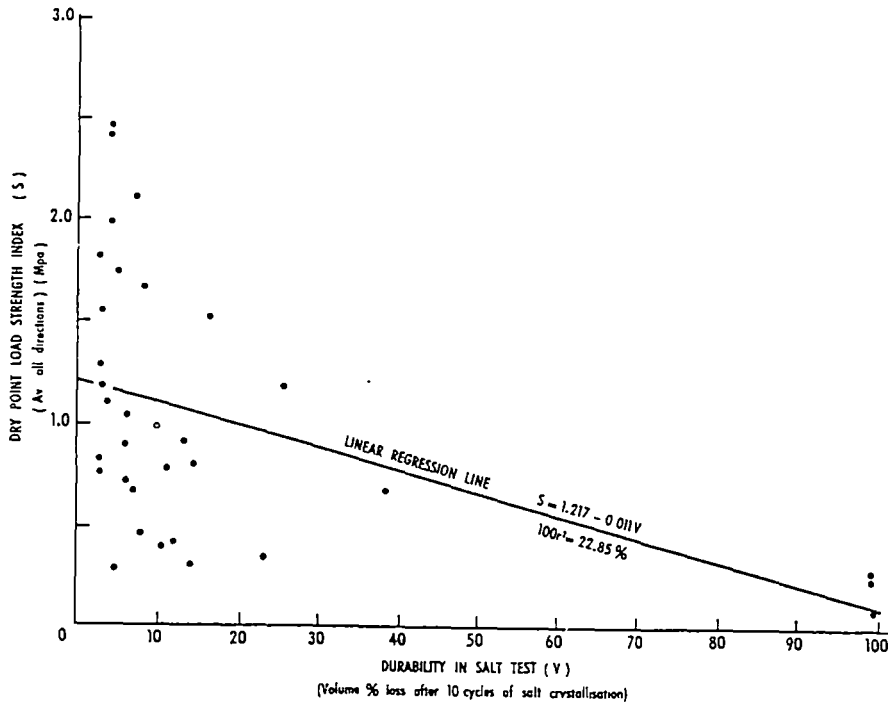


Fig. (B:5.3.1)a

Figs (B:5.3.1)a, b, c

These three diagrams show the degree of correlation between each of the three major sandstone properties, taken in turn, and the actual durability of sandstone when subjected to the cyclic salt crystallisation test.

Thirty four specimens are used in each case, these being the 34 on which all relevant tests and regression analysis have been done.

The figure of $100 r^2$ refers to the percentage of variance in actual durability which is correlated with variance in the other property plotted in each case. (That is, $100 r^2$ is a measure of what percentage of variation in durability can be attributed to the influence of the particular property in question).

As these three plots clearly show, no one sandstone property taken alone can account for more than 22.85% of the influence on the observed durability of the sandstone in the salt test.

Fig. (B:5.3.1)a

Correlation of Dry Point Load Strength Index with actual durability of the specimens when subjected to the cyclic salt test.

Fig. (B:5.3.1)b

Correlation of Effective Porosity with actual durability of the specimens when subjected to the cyclic salt test.

Fig. (B:5.3.1)c

Correlation of Detrimental (Swelling) clay content with actual durability of the specimens when subjected to the cyclic salt test. In this case, the regression line (i.e. 'line of best fit') has a slope opposed to that which one would theoretically expect of there was any correlation at all. In this case, therefore, it can be said there is no correlation at all between detrimental clay content (taken by itself) and the actual durability of stone subjected to the cyclic salt test.

215.

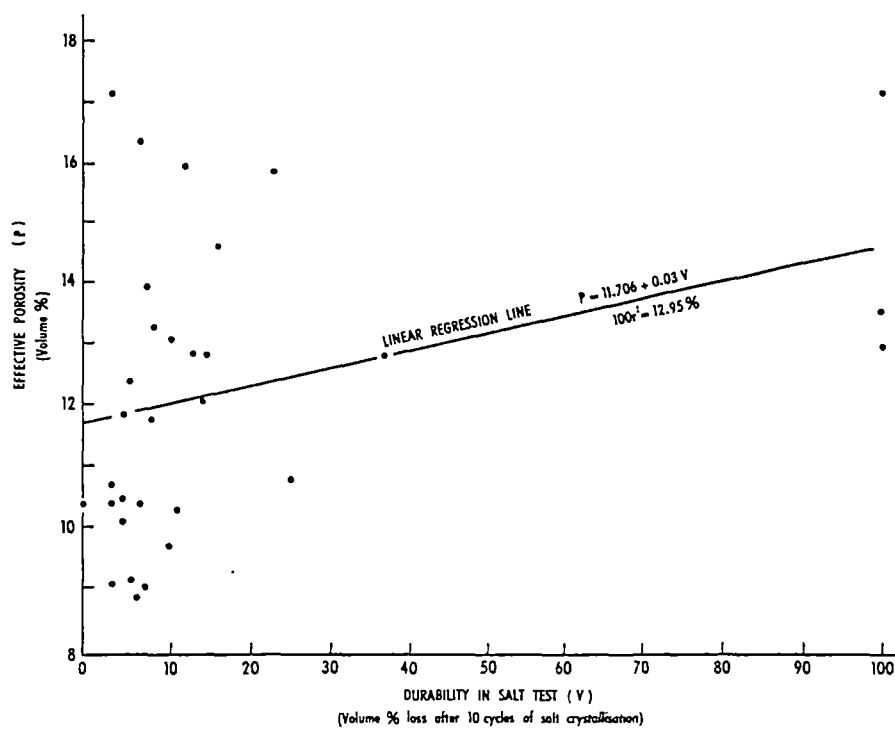


Fig. (B:5.3.1)b

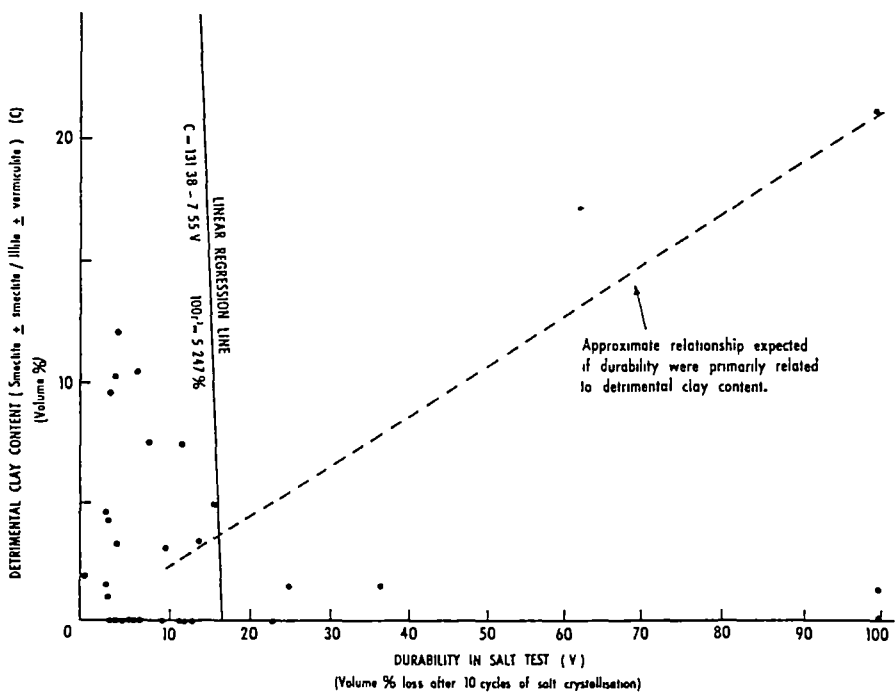


Fig. (B:5.3.1)c

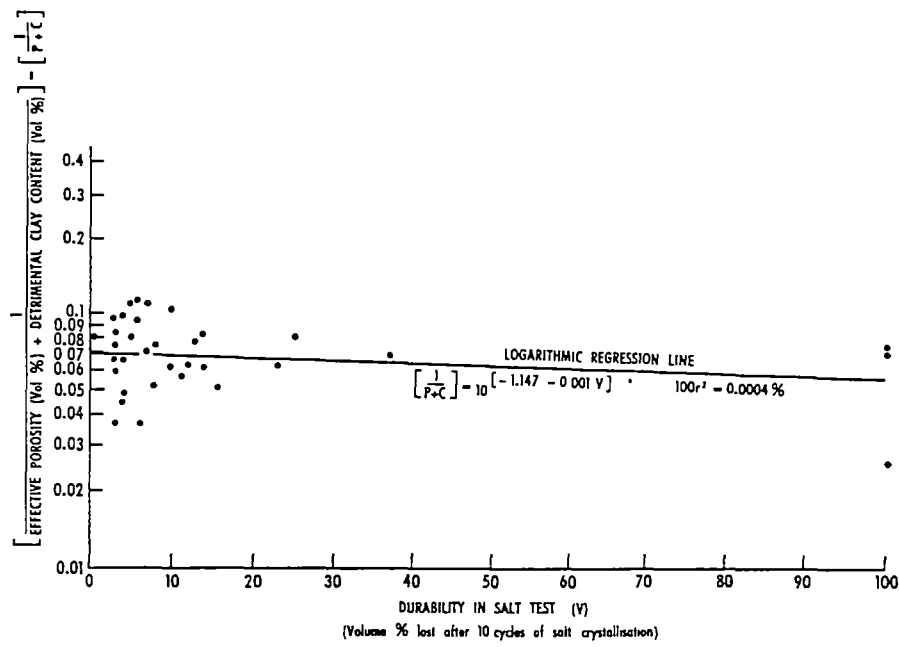


Fig. (B:5.3.2)a

Correlation of the combination of Effective Porosity and Detrimental (Swelling) clay content with actual durability of 34 tested specimens in the cyclic salt test. The near-horizontal regression line and tiny 100 r^2 value indicate that the combination of these two parameters is useless as a predictor of actual durability.

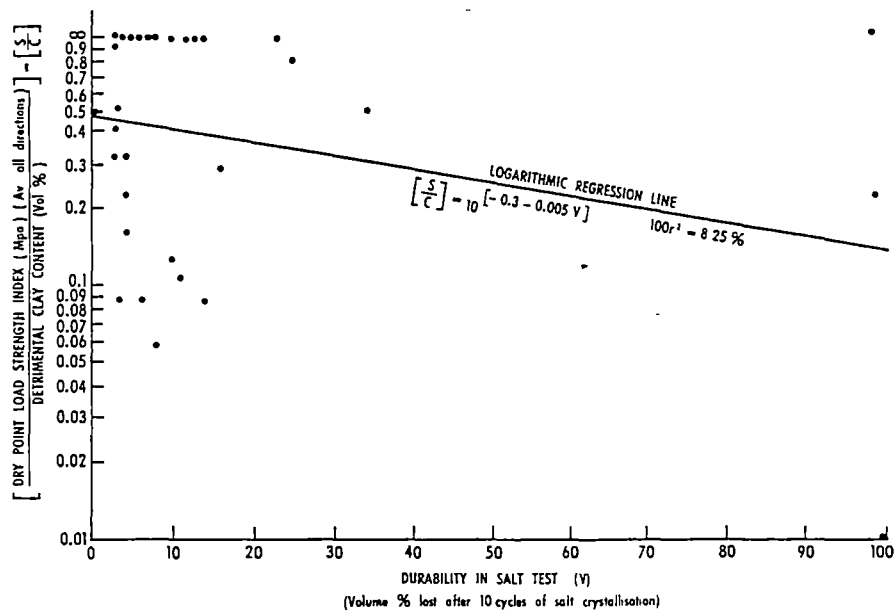


Fig. (B:5.3.2)b

Correlation of the combination of Strength and Detrimental (Swelling) clay content with actual durability of 34 tested specimens in the cyclic salt test. The degree of correlation (8.25% of the variation in actual durability can be attributed to the combination of strength and detrimental clay content) is negligible.

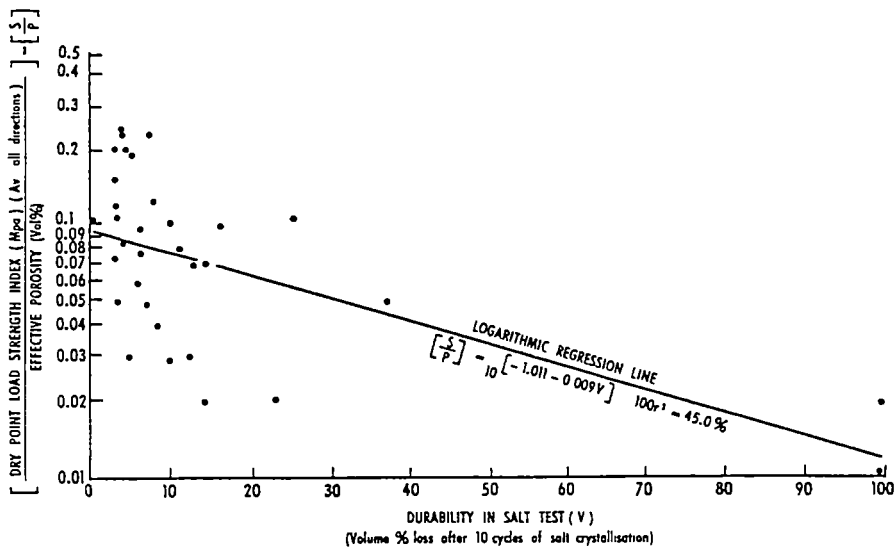


Fig. (B:5.3.3)a

Correlation of the combined effects of Strength and Effective Porosity with actual durability of 34 tested specimens in the cyclic salt test. The correlation ($100 r^2$) of 45% indicates these two factors have a strong influence on sandstone durability when subject to the sort of stress involved in the cyclic salt test.

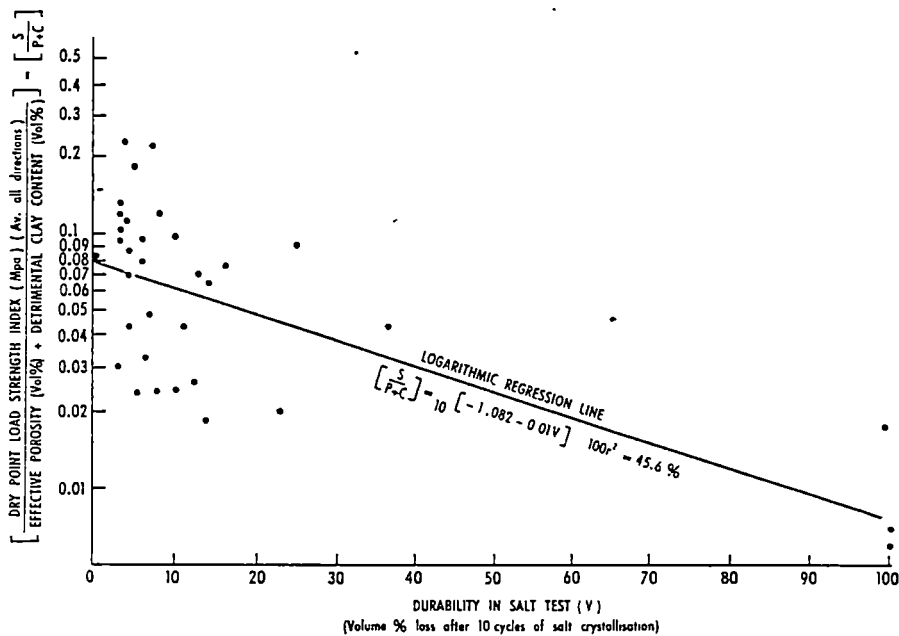


Fig. (B:5.3.3)b Correlation of the combined effects of Strength, Effective Porosity and Detrimental (Swelling) clay content with actual durability of 34 tested specimens in the cyclic salt test. The correlation ($100 r^2$) of 45.6% is almost identical to the correlation when only strength and porosity are considered. Together with the fact that detrimental clay content alone has no correlation at all to actual durability (see Fig. B:5.3.1c) this indicates that under the specialised conditions of this sort of short term, high stress, cyclic salt test, strength and porosity are important in determining durability, while detrimental clay content appears to have little effect.

218.

The most important conclusion to be drawn from attempting to individually correlate the three major properties with the durability of specimens in the salt test is that none of the properties taken alone are of any real use in predicting or accounting for the specimens durability in the salt test. Point load strength taken alone gives the best correlation with durability, at 22.85%, but even this is far too low to be useful in predicting durability.

Such results are not surprising. As proposed in Section (B:3.3) it is to be expected that the durability of stone would be the resultant of the interacting effects of several properties, rather than the outcome of just one major property.

The following procedure was adopted to test various combinations of the properties, S, P and C against durability in the salt test (V).

- (1) Functions were defined combining S, P and C in such a way that the resultant predicted durability would increase as S (point load strength) increases, but decrease as P (effective porosity) and/or C (detrimental clay content) increased. The four possible combinations of S, P and C in accordance with this condition are:

S/C - assuming only strength and detrimental clay content to be important

S/P - assuming only strength and effective porosity to be important.

1/P+C - assuming only effective porosity and detrimental clay content to be important.

S/P+C - assuming all three major properties to be important.

These four functions constitute the simplest ways of relating the various properties. It could be that better durability prediction could be obtained through arithmetical refinements (e.g. $\frac{2.55}{1.37P+C}$ might give better results than $\frac{S}{P+C}$), but at the present stage of this work it is only possible to assume the simplest form of the functions being tested.

- (2) The values for each of the four functions were calculated for the 34 specimens (See Table B:5.3.1) and plotted against durability in the salt test (Figs (B:5.3.2) and (B:5.3.3)). Regression analysis and calculation of 100 r^2 were performed again to find how

219.

well each of the four proposed durability functions correlated with measured durability in the salt test. Results were plotted on both linear and logarithmic graph paper, and visual inspection seemed to indicate that the relationship between the predicted durability functions and the actual durabilities in the salt test were more logarithmic than linear. A logarithmic relationship is one of the simplest non-linear relationships possible, and was accepted for this work as the best model for the relationships being investigated. Of course, it may be possible to refine the model of a simple logarithmic relationship but that cannot yet be done on the basis of work to date.

Unlike the linear relationships obtained when S, P and C were individually compared with V, non-linear (logarithmic) relationships emerge because several properties are combined in a single function of predicted durability.

Since the nature of a logarithmic relationship is that it appears linear when the data is plotted as logarithms, logarithmic regression lines and correlation co-efficient can be obtained by converting the predicted durability functions to logarithms, performing ordinary linear regression analysis on the logarithms, and then converting the results back into non-logarithmic form.

In order to test the subjective assertion that the data was related logarithmically rather than linearly, both linear and logarithmic regression analysis was performed on the data from the most successful predicted durability function, S/P+C (see below). The correlation ($100 r^2$) obtained from the logarithmic regression (45.6%) was much better than that obtained from the linear regression (15.464%) indicating that a logarithmic relationship clearly fits the data much better than a linear one.

The results of the logarithmic regression analysis of the four alternative predicted durability functions are presented on Table (B:5.3.2).

It is noteworthy that the best results - the best predicted durability function - still only give a correlation with actual durability in the salt test of less than 50% ($100r^2$). This may be due to any or all of the following factors:

- (1) Other fundamental properties may be involved in addition to the three major ones considered here.
- (2) Minor inaccuracies are possible in the measured values of detrimental clay content, point load strength and volume % loss in the salt test.

220.

- (3) The predicted durability functions may need refinement, and their relationship to actual durability may not be completely logarithmic.
- (4) Most of the specimens were in the high durability range - a wider spread of specimens from high to low durability might have allowed better regression analysis.

Although it will require the collection of further data to resolve these uncertainties, it is nonetheless clear that the results obtained to date do give valid information about the usefulness relative to each other of the alternative possible functions for predicting durability.

The following conclusions can be drawn:

- (1) Consideration of Effective Porosity together with detrimental clay content, but without consideration of rock strength ($\frac{1}{P+C}$), yields a function having no relationship to durability of all ($100r^2 = 0.0004\%$). The regression line is nearly horizontal with respect to durability, indicating no necessary change in durability with change in ($\frac{1}{P+C}$). (Fig. B:5.3.2a).

This result is predictable from theoretical considerations:- effective porosity and detrimental clay content both enhance stone decay, but until we know the strength of the rock we cannot know to what extent that decay will be resisted.

It is thus indispensable to include the strength of the rock in all calculations of rock durability.

- (2) Consideration only of the interaction of strength and detrimental clay content also yields a function (S/C) having almost no relationship to durability in the salt test ($100r^2=8.25\%$). (Fig. B:5.3.2b).
- (3) Consideration only of the interaction of strength and effective porosity yields a function (S/P) whose correlation with durability in the salt test ($100r^2 = 45.0\%$) is almost as good as the best function (below). (Fig. B:5.3.3a).
- (4) Consideration of the interaction of all three major properties, strength, effective porosity and detrimental clay content, yields a function ($S/P+C$) whose correlation with durability in the salt test ($100r^2 = 45.6\%$) is the best obtained from any of the alternative predicted durability functions (Fig. B:5.3.3b). It is noteworthy however, that the improvement in correlation from $S/P+C$ as compared with S/P is so marginal as to not be meaningful.

221.

(B:5.3.4) Significance of the results

The overall significance of these results is that one can confidently assert the following propositions:

- (1) The durability of stone cannot be even approximately predicted without taking into account the strength of the rock. It is rock strength which determines the degree of resistance rock has to decay processes which other properties of the rock may facilitate.
- (2) The content of detrimental clays (i.e. swelling clays-smectites and vermiculites) in the rock has NO direct effect on the durability of the rock when exposed to the conditions of the cyclic salt crystallisation effect. This is demonstrated by the fact that whereas consideration of strength and effective porosity (S/P) give as good a prediction of durability in the test as is possible, addition of detrimental clay content (S/P+C) makes no real improvement to durability prediction. In addition, consideration of strength and detrimental clay content without consideration of effective porosity (S/C) gives a very poor prediction of durability in the salt test.
- (3) The main identifiable determinants of sandstone durability under the conditions of the cyclic salt crystallisation test are strength and effective porosity.

These are very important conclusions. There are good theoretical and practical reasons to think that detrimental (swelling) clay content does in fact have a significant effect on the durability of Tasmanian sandstones exposed to the particular conditions of the Tasmanian building environment. However, the results discussed above indicate that THE CYCLIC SALT CRYSTALLISATION TEST GIVES NO DIRECT INDICATION OF HOW DURABLE A STONE BEARING DETRIMENTAL (SWELLING) CLAYS WILL ACTUALLY BE IN THE BUILDING ENVIRONMENT.

It seems that the cyclic salt test essentially duplicates, in speeded up form, the effects of salt attack, which is of course a severe stone decay problem. As far as mainland sandstones, which generally do not contain detrimental clays, are concerned, this test should be an adequate test of stone durability. However, for Tasmanian sandstones, with their high content of detrimental clays, it has to be recognised that the cyclic salt test does not properly evaluate a stones response to wet-dry cycles which can, over a period of time, cause the detrimental clays to facilitate decay of the stone.

222.

It is probable that the cyclic salt test is not informative in this latter respect because 24 hr wetting and drying cycles do not cause the detrimental clays to swell and contract sufficiently to cause damage. Only over longer periods in actual building environments will the effects of the clays swelling and shrinking behaviour become apparent.

Recognition of this limitation of cyclic salt tests explains anomalies such as that noted by Spry (1983, p. 56) who notes that although the Linden Sandstone performs very well in a sodium sulphate test, it nonetheless shows some decay after a year or two in use. This decay is due to the presence of about 4% smectite clay in the stone.

A final complication worth noting is that it was found that in the samples studied in these tests, the specimens with the highest detrimental clay contents did in fact have low strengths and high porosities, thus causing them to perform badly in the salt test. Whether this is mere co-incidence or whether there is any causal relationship between high detrimental clay content and low strength/high porosity is uncertain. It is possible that high detrimental clay content causes lower strength due to the overall clay content of the stone being higher (Point Counting does in fact indicate that some of the stones with high detrimental clay content have higher overall clay content - e.g. Green Kangaroo Point Sandstone, "Trinity 2", and some Port Arthur Specimens). High Detrimental clay content could also cause apparent increased effective porosity due to water absorption in the crystal structure of the detrimental clays themselves.

In such cases, high detrimental clay content can cause low durabilities in the salt test, but only indirectly through lowering strength and increasing porosity, not directly through the mechanical effects of swelling and shrinking clays. However, since these indirect effects of the detrimental clays only seem to be notable when the clays are in very high concentrations, the general conclusion that detrimental clay content has no direct effect on the results of cyclic salt testing is still valid. Detrimental clay content is a variable whose effect should be considered in its own right, in addition to the results of the salt test, even though in some cases very high detrimental clay contents may indirectly affect a sandstone's response to the salt test.

APPENDIX EIGHT

TASMANIAN EARLY TRIASSIC SANDSTONES: DATA COLLECTED DURING PRIVATE EXPLORATION WORK

The following data was collected during sandstone exploration work conducted on behalf of Rizzolo Stone & Concrete P/L during 1987-88 (used by permission of Mr Peter Rizzolo), and the Tasmanian Development Authority in 1989. Most sites are within the Hobart, Brighton and Oatlands quadrangles, plus a few immediately adjacent areas.

The data is relevant to discussions in Chapter Seven. The following comments are relevant to interpretation of the data:

1) Site Number

The system of site numbering is that which was developed for the exploration work referred to above (see Sharples 1990). The list of sites is incomplete, since it does not include sites to which only a cursory examination was given (the stone being clearly inferior), and does not include a number of Permian outcrops which were examined.

2) Grid Reference

As per AMG map grid references used throughout this work.

3) Stratigraphic unit

Mapped unit designation as per Geological Survey 1:50,000 Geological Atlas sheets.

4) Bulk colouration

See Section (2.4.2). Note that this data is biased towards stone of brown bulk colouration, since that is the colouration which was being explored for. On the data sheet, "gr-wh" refers to "grey - white" bulk colouration.

5) Patterned Fe-staining

Includes Liesegang rings, irregular blotches, bands and other iron-oxide patterns OTHER THAN uniform brown iron-oxide bulk colouration. Note also that this data is somewhat biased towards outcrops with minimal staining, since the exploration was aimed at finding uniformly coloured stone. Superficial reddening of the outer case-hardened layer of outcrops is not recorded or considered.

Recorded in terms of semi-quantitatively defined degrees of iron-staining intensity, as follows:

Strong:	Intensely coloured staining, occurring in >50% of stone bulk volume.
Moderate:	Moderately dark staining occupies approx. 50 -10% of bulk volume.
Minor:	Staining present in <10% of bulk volume, often moderate to pale brown.
Absent:	Uniform bulk colouration only.

6) Distance from dolerite

Dolerite rather than basalt is invariably the closest igneous intrusive rock to the sites studied.

7) Clay Types

In some cases clay types have not been determined, where other characteristics quickly ruled the stone concerned out of consideration for building purposes. In cases where clay types were determined, this was done primarily to check for the presence of smectite; hence in many cases no was a differentiation was made between vermiculite and chlorite, since this requires an extra stage in the XRD analysis procedure.

Site No.	Grd Ref.	Strat. Unit	Bulk colour	Patterned Fe-stains	NEAREST SURFACE DOLERITE CONTACT			CLAY TYPES PRESENT (if determined)			
					Distance	Intrusive	Post-dolomite fault intervenes	illite	kaolinite	smectite [%]	vermiculite or chlorite
S/Ts/1/1	EN124613	Rls	gr-wh	Strong	1.0 km		X	X	X		
S/Ts/5/3	DN967636	Rls	brown	absent	500 m ?	?		X			
S/Ts/6/1	EN027677	Rls	brown	minor	300 m	X		X	X	X[47]	
S/Ts/8/1	EN038808	Rls	brown	absent	300 m	X		X			X
S/Ts/9/1	EN011850	Rls	brown	absent	800 m		X	-	-	-	-
S/Ts/10/1	EN145843	Rls	brown	minor	1.3 km		X	X	X	X[1]	
S/Ts/10/2	EN149853	Rls	brown	minor	100 m	X		X		X[26]	X
S/Ts/12/1	EN073867	Rls	brown	absent	1.5 km	X		X	X		X
S/Ts/12/1	EN069865	Rls	brown	absent	1.5 km	X		X	X	X[5]	X
S/Ts/12/2	EN072889	Rls	brown	absent	800 m		X	X	X		X
S/Ts/12/3	EN071885	Rls	brown	absent	1.0 km		X	X	X		X
S/Ts/14/1	EN389821	Rls	brown	moderate	300 m	X		-	-	-	-
S/Ts/20/2	EN117417	Rls	brown	absent	1.0 km	X		X	X		X
S/Ts/23/1	DN970780	Ross	brown	moderate	100 m	X		-	-	-	-
S/Ts/24/1	EN152981	Rp	brown	absent	1.5 km	X		X	X		X
S/Ts/28/1	EP345030	Rls	brown	minor	1.5 km		X	X	X		
S/Ts/30/1	EN244964	Rp	gr-wh	minor	1.0 km		X	X	X		X
S/Ts/30/2	EN237976	Rp	brown	minor	200 m	X		-	-	-	-
S/Ts/31/1	EN098910	Rp	brown	moderate	1.0 km	X		X	X		
S/Ts/32/2	EP314164	Ru	brown	absent	1.2 km	X		X			
S/Ts/37/1	EN361962	Rls	gr-wh	strong	3.0 km		X	X	X		
S/Ts/43/1	EN295754	Rlq	brown	minor	600 m	X		X	X	X[9]	X
S/Ts/43/2	EN299755	Rlq	brown	minor	800m	X		X		X[46]	
S/Ts/43/7	EN309757	Rlq	gr-wh	minor	600 m	X		X	X	X[2]	
S/Ts/44/1	EN590630	Rss	brown	minor	300m	X		X	X	X[76]	
S/Ts/47/1	EN156415	Rlq	gr-wh	strong	250 m	X		X	X		
S/Ts/47/2	EN155417	Rlq	gr-wh	absent	400 m	X		X	X		
S/Ts/49/1	EN128748	Rlq	gr-wh	strong	500 m	X		-	-	-	-
S/Ts/50/1	EN066843	Rls	brown	minor	300 m	X		X	X		
S/Ts/51/1	EN067828	Rls	brown	minor	300 m	X		X	X		X
S/Ts/54/2	EN315798	Rls	gr-wh	moderate	100 m	X		-	-	-	-
S/Ts/57/1	EN113844	RI	brown	minor	1.7 km		X	X	X	X[14]	
S/Ts/59/1	EN023123	Rs	gr-wh	minor	1.0 km	X		X	X		
S/Ts/60/1	EN554631	Rss	gr-wh (green)	moderate	100 m	X		X		X[95]	
S/Tn/3/1	EQ424011	Rq	brown	absent	1.3 km	X?		X	X		X
S/Tn/3/2	EQ432006	Rq	brown	absent	700 m	X?		X	X	X[88]	X
S/Tn/3/3	EQ393009	E. Tr.	brown	moderate	200 m	X		X	X		X

NOTES: [*] - Volume % of total clay content, averaged over all samples.
 - - Not determined
 E. Tr. - Early Triassic
 Ross - Ross Sandstone (Early Triassic)

APPENDIX NINE

TASMANIAN EARLY TRIASSIC SANDSTONES: DATA ABSTRACTED FROM APPENDIX ONE

The following data has been abstracted from Appendix One for the purpose of the discussions detailed in Chapter Seven. Sandstone sources of geological age other than Early Triassic, or for which sufficient data is not available, have been omitted.

See Appendix Eight for explanatory notes.

Since this data refers to sources of sandstone which have been used for building purposes, it is inevitable that it will be biased towards sandstones whose colouration has been considered "attractive". Naturally, "unattractive" sandstones are just as important in understanding the causes of sandstone colouration, but time and resources during this project have not permitted a truly comprehensive and unbiased sampling of sandstone types.

Site No.	Grd Ref.	Strat. Unit	Bulk colour	Patterned Fe-stains	NEAREST SURFACE DOLERITE CONTACT			CLAY TYPES		PRESENT (if determined)	
					Distance	Intrusive	Post-dolerite fault intervenes	illite	kaolinite	smectite [%]	vermiculite or chlorite
1	EN682224	E. Tr.	brown	minor	200 m	X ?		X		X [87]	
2	EN680213	E. Tr.	brown	absent	500 m	X ?		X		X[50?]	
3	EN683186	E. Tr.	brown	absent	1.0 km	X ?		X		X [17]	
4	EN300528	Rls	gr-wh (green)	minor	50 m		X	X	X	X [54]	X (trace chlorite)
5	EN313535	Rlq	gr-wh	minor	200 m	X		X	X	X [2]	
6	EN304551	Rlq	brown	minor	-	-	-	X	X	X [75]	
7	EN271536	Rl	brown	minor	100 m		X	X	X	X [30]	
8	EN247523	E. Tr.	gr-wh	minor	40 m	X		X	X	X [13]	
9	EN233490	Rls	gr-wh	minor	80 m	X		X			
11	EN295561	Rlq	brown	absent	400 m		X	-	-	-	-
12	EN152002	E. Tr.	gr-wh	minor	3.0 km	X ?		X	X	X [9]	
13	EN267730	Rlq	gr-wh	absent	250 m	X#	X#	X	X	X [7]	
14	EN787906	E. Tr.	gr-wh	strong	100 m	X		X	X		
15	EN744864	E. Tr.	gr-wh	moderate	1.0 km	X		X	X		
16A	EP413459	E. Tr.	gr-wh	strong	300 m	X		X	X		(4 quarries, all smectite-free)
17	EP018058	Rp	gr-wh	moderate	150 m	X		X	X		
21	EN220734	Rls	gr-wh	strong	150 m	X		X	X	X [3]	
22	EN219733	Rls	gr-wh	absent	150 m	X		X	X	X [1]	
23	EN158705	Rls	brown	minor	1.0 km		X	X	X	X [3]	
24	EP297152	E. Tr.	brown	absent	2.0 km	X		X	X	X [2]	X(vermic.)
26	EN088827	Rls	brown	absent	200 m		X	X	X		X (vermic.)
27	DN999650	Rls	brown	moderate	500 m		X	X	X	X [11]	X(chlorite)
28	EN575880	E. Tr.	gr-wh	strong	200 m	X		X	X		
29	EN106603	Rls	gr-wh	strong	300 m	X		X	X		
30	EP236239	Rp	gr-wh	strong	300 m	X		X	X		
31	EN265425	Rls	gr-wh	strong	100 m	X		X			
32	EP0407	Rp	gr-wh	moderate	200 m	X		X	X	X [1]	
33	EN336763	Rlq	gr-wh	strong	300 m		X	X	X	X [3]	
34	EN153979	Rp	brown	absent	1.0 km	X		X	X		X(vermic.)
38	EN072576	Rls	gr-wh	strong	100 m	X		X	X		

NOTES: E. Tr. - Early Triassic
 # - See discussion in Section (7.6.4 C)
 [*] - Volume % of total clay, averaged over all samples.
 - - Data not recorded.

APPENDIX TEN

QUARTZ SANDSTONE SEQUENCE: JOINT SPACINGS

This appendix lists joint spacing data for all quarries and outcrops in the Early Triassic Quartz Sandstone Sequence for which such data was recorded during the course of this project.

The data for quarries is abstracted from Appendix One, and the same source numbers are given. The data on other outcrops was collected during consulting exploration work on behalf of Rizzolo Stone and Concrete Pty Ltd (1987-88), and the Tasmanian Development Authority (1989). The site numbering system employed was developed during the consulting work, and is explained in Sharples (1990).

QUARRIES

<u>SOURCE No.</u>	<u>AMG Grid Reference</u>	<u>JOINT SPACINGS (metres)</u>
2	EN680213	2.0
3	EN683186	<1.0
4	EN300528	0.1 - 1.5
5	EN313535	2.0 - 3.0
9	EN233490	<2.0
12	EN152002	3.0
13	EN267730	<10.0
14	EN787906	<1.0 - 2.0
15	EN744864	1.0 - 6.0
16	EP413459	2.0 - 4.0
17	EP018058	1.0 - 3.0
21	EN220734	<0.5 - >2.0
22	EN219733	1.0 - 3.0
23	EN158703	<1.0
24	EP297152	3.0 - 7.0
26	EN088827	5.0 - 15.0
27	DN999650	<1.0 - 4.0
28	EN575880	10.0 - 30.0
29	EN106603	1.0 - 3.0
30	EP236239	4.0 - 5.0
31	EN265425	0.1 - 1.0
33	EN336763	1.0 - 6.0
34	EN153979	1.0 - 5.0
38	EN072576	1.0 - 2.0

OUTCROPS

OUTCROP SITE No. AMG Grid Reference JOINT SPACINGS (metres)

S/Ts/1/1	EN124613	>10.0
S/Ts/5/3	DN967636	>3.0
S/Ts/6/1	EN027677	1.0
S/Ts/8/1	EN038806	1.0 - 1.5
S/Ts/10/1	EN145843	2.0 - >3.0
S/Ts/10/2	EN149858	>3.0
S/Ts/12/1	EN073867	>5.0
S/Ts/14/1	EN389821	<1.0 - 2.0
S/Ts/20/1	EN084413	<3.0
S/Ts/20/2	EN117417	3.0 - 4.0
S/Ts/23/1	DN969779	>1.0
S/Ts/23/3	DN954853	>1.0
S/Ts/28/1	EP345030	1.0 - 2.0
S/Ts/30/1	EN244964	<3.0
S/Ts/30/2	EN237977	<2.0
S/Ts/31/1	EN098910	>5.0
S/Ts/32/2	EP314164	3.0 - >10.0
S/Ts/37/1	EN361961	>2.0
S/Ts/43/1	EN295754	2.0 - 3.0
S/Ts/44/1	EN590630	2.0
S/Ts/46/1	EN660565	<1.0
S/Ts/47/1	EN156415	1.0 - 4.0
S/Ts/47/2	EN155417	4.0
S/Ts/49/1	EN128748	<0.5
S/Ts/51/1	EN067828	>5.0
S/Ts/57/1	EN113844	>10.0
S/Ts/59/1	EN023123	<1.0 - 3.0
S/Ts/59/4	EN025117	5.0 - 6.0
S/Ts/60/1	EN554631	2.0
S/Ts/64 (area)	Osterley - Strickland	>3.0
S/Ts/67 (area)	SE of Woodsdale	>3.0
S/Tn/3/1	EQ424011	2.0 - 9.0
S/Tn/3/3	EQ393009	>10.0

APPENDIX ELEVEN**DISTRIBUTION OF CLAY TYPES, HALITE AND GYPSUM IN EARLY
TRIASSIC SANDSTONES DRILLED NEAR BOTHWELL**

This appendix is a copy of Sharples (1984: Tas. Dept. Mines Unpubl. Rept. 1984/27), and is referred to in several places within this thesis.

1984/27. Distribution of clay types, halite and gypsum in early Triassic sandstones drilled near Bothwell

C.E. Sharples

Abstract

The distribution of clay types, halite and gypsum in a 245 m section of early Triassic sandstone drilled at Bothwell has been determined using XRD analysis of the core at two metre intervals. Illite plus kaolinite are dominant in the matrix of most of the sandstone, but mixed-layer illite/smectite also occurs commonly throughout the 245 m section. Chlorite is also present at two horizons. The relationship of clay, halite and gypsum distribution patterns to the occurrence of weathering zones and probable aquifers in the drill hole, provides "circumstantial" evidence that, to a significant degree, the distribution of the clays and the halite and gypsum are related to the diagenesis and weathering history of the sandstones rather than to their original depositional composition.

INTRODUCTION

During work on a project studying the factors involved in the durability of Tasmanian sandstones in building usage, it was found that the types and proportions of clays in sandstone matrices play an extremely important role in determining the durability. It was realised that it would be very useful to gain some knowledge of how clay types and proportions vary with stratigraphic position within the sandstone at a single locality. As most sandstones used for building in Tasmania, are early Triassic (Upper Permian Super-Group) sandstones from eastern Tasmania, it was decided to sample and test a diamond-drill hole through a significant thickness of early Triassic sandstones.

During 1983, the Department of Mines drilled a deep diamond-drill hole (DDH 'THORPE') near Bothwell in the southern Central Plateau region of Tasmania. Drilling and lithological logging of the hole was supervised and performed by R.C. Donaldson and S.M. Forsyth. The upper part of the hole cored approximately 230 m of early Triassic quartz arenite before passing into a correlate of the Cygnet Coal Measures.

This hole was chosen as suitable for testing clay matrix variations with stratigraphic position as it cored a large proportion of the early Triassic sandstone and was not disrupted by faulting or igneous intrusions.

GEOLOGICAL SETTING

The hole was sited approximately three kilometres ESE of Bothwell township at EP035060. The hole was collared at 392.3 m above sea level, in an area mapped by Forsyth et al. (1976) as Triassic quartz sandstone (Rp). Revised mapping of the drill hole site indicates the collar occurs immediately above Rp in "micaceous mudstone and interbedded micaceous, frequently muddy, quartzose sandstone of very fine to fine grain size. Interbedded minor red beds, carbonaceous mudstone" (Rm - S.M. Forsyth, pers. comm.).

At approximately 13.5 m below the surface the hole passed into the unit mapped in the Oatlands Quadrangle as Rp, defined by Forsyth et al. (1976) as "quartzose sandstone of very fine to medium grain size, fining upward, with interbedded siltstone and clay pellet beds". Mudstone horizons, micaceous sandstone, occasional minor red beds, and carbonaceous mudstone also occur.

At 234.2 m below the surface the hole passed into rock of the Cygnet Coal Measures Correlate (Pj). The hole terminated in the Lower Parmeener Super-Group at 763 m depth.

On the surface the nearest igneous intrusions (Jurassic dolerite) are over 0.5 km distant, and the nearest mapped fault is a dolerite-filled fault running north-south one kilometre to the east of the drill hole. The hole was sited in the middle of a large gravity low anomaly, which is indicative of the area being free of major igneous intrusions. There is no evidence of major faulting or igneous intrusions affecting the Triassic rocks drilled in DDH 'Thorpe'.

TESTING PROCEDURES

Small samples were taken from the core at precise two metre intervals down to a depth of 245 metres. The clay fraction in each sample was separated according to the method of Carroll (1970) and the clay types present determined by X-ray diffraction. Absolute percentages of each clay mineral within the total rock were not determined. However, a useful measure of the percentage of each clay mineral in the total clay matrix of each sample was obtained by simply comparing the heights of the main XRD peaks for each clay mineral in the given sample. This procedure is based on that of Carroll (1970) who presented a method for comparing clay percentages based on the area beneath XRD peaks. Preparation and testing of standard clay mixtures showed that this method gives results which, although only approximate, nevertheless give consistent indications of the relative proportions of the various clay minerals in a given sample.

The approximate percentages can be taken as either approximate volume or mass percentages, as the commonest clay minerals encountered (illite, kaolinite, smectite and chlorite) have variable and overlapping densities.

Clay proportions obtained in this way are not directly comparable in absolute terms between different samples, but do give useful indications of the trends in the abundance of various clays through the drill hole.

Gypsum and halite were also detected by the XRD analysis, and are included in the results. However, the solubility of these minerals means that slight variations in the preparation of samples could result in major variations in the size of their XRD peaks. Therefore, it is not possible, by XRD techniques, to determine the proportions of gypsum and halite in the samples - they are simply recorded as being present or absent.

RESULTS

The results of the testing are presented graphically in Figure 1. The lithological log prepared by S.M. Forsyth and R.C. Donaldson, and the core fracturing log prepared to a depth of 160 m by R.C. Donaldson, are also included. The significance of the fracture log is that fracture density is related to groundwater movements which, in turn, may be related to diagenetic changes influencing the mineralogy of the sandstones drilled.

By reference to the drillers log and by consultation with Baroid, the manufacturers of the drilling muds used in DDH 'Thorpe', it was determined that the drilling muds used contained only organic polymers with a mineral oil carrier. Thus, the smectite and gypsum found in the drill core are real components of the sediments, and not merely contamination from drilling muds containing bentonite or gypsum.

SIGNIFICANCE OF THE RESULTS

This work is part of an ongoing investigation, and it is not appropriate at this point to attempt to present a detailed discussion of the significance of the results. However, the following points appear to have been established:

- (1) Smectite occurs intermittently throughout early Triassic quartz arenites at Bothwell. In conjunction with data being obtained from quarries throughout eastern Tasmania by the author, it would appear that this pattern is typical of most early Triassic sandstones in Tasmania.
- (2) The smectite usually occurs as mixed layer illite/smectite, rather than as pure smectite. This also concurs with other data from eastern Tasmania.
- (3) In a number of instances, it appears that the occurrence of clays, halite and gypsum is related to groundwater movements, and thus to diagenetic rather than depositional circumstances. The clearest examples include:
 - (a) An anomalous interval which appears to be related to the largest fracture zone (and largest aquifer?) in the hole, at 101 m to 107 m depth, and which also has a number of lesser fractured zones and zones logged by R.C. Donaldson as "slightly weathered" due to slight colouration. Within this interval smectite is almost totally absent in zones above and below the main fracture zone at 01-107 m; the main halite zone in the hole occurs above the major fracture zone and could be the result of halite precipitating from groundwater moving upwards from the fracture zone; and finally, whereas illite and kaolinite both occur together throughout most of the sampled part of the hole, and usually in roughly similar proportions, between 95 m and 153 m illite is a very minor component of the sandstone matrices, and kaolinite is dominant, often showing large narrow peaks on the XRD trace which indicate a well-ordered crystal structure.
 - (b) The occurrence of significant gypsum in two bands at 173-187 m depth and 218-222 m depth, both of which appear to be permeable horizons enclosed above and below by less permeable lutite beds.
- (4) Chlorite occurs in two zones in the hole. The first, from 5 m to 59 m depth, appears to be a surface weathering effect. The second zone, at 153 m to 173 m depth, corresponds to the thickest lutite band logged in the top 250 m of the hole, and may therefore represent the depositional composition of that bed, or result from diagenetic alteration of a bed whose depositional composition was different to the rest of the sediments sampled.

CONCLUSION

The Bothwell DDH 'Thorpe' has provided circumstantial evidence indicating that the clay, halite and gypsum composition of Tasmanian early Triassic sandstones may be related as much to diagenetic and weathering effects as to original deposition. However, further work involving detailed

examinations of the chemical interactions between the various minerals involved and the groundwater will be required before such a conclusion can be established.

REFERENCES

- CARROLL, D. 1970. Clay minerals: A guide to their X-ray identification. *Spec.Pap.geol.Soc.Amer.* 126.
- FORSYTH, S.M.; ABTMAIER, B.F.; LEAMAN, D.E. 1976. Geological atlas 1:50 000 series. Zone 7 Sheet 68 (8313S). Oatlands. *Department of Mines, Tasmania.*

[2 May 1984]

CLAYS, HALITE AND GYPSUM DISTRIBUTION IN TRIASSIC SANDSTONES, BOTHWELL, DDH "THORPE"

Lithological log courtesy of S Forsyth and R Donaldson Fracturing and possible fissure aquifers logged to 160 metres depth by R Donaldson



APPENDIX TWELVE

SCANNING ELECTRON MICROSCOPY: CLAYS IN TASMANIAN BUILDING SANDSTONES

This appendix presents a summary of information collected in the course of a Scanning Electron Microscope (SEM) study of clays in Tasmanian building sandstones conducted during this project. The study was conducted using facilities at the Central Science Laboratory of the University of Tasmania.

The primary aim was determine the nature (detrital or authigenic) of the clays. The study was purely qualitative; no attempt has been made to determine the relative proportions of authigenic and detrital clays in each specimen; only the presence or absence of each type was recorded. However, relative proportions of each clay mineral present was determined during XRD studies of the same specimens (Appendix One), and this information is presented along with the SEM data.

Sandstone source and specimen numbers are as used in Appendix One. The following abbreviations are used to record data:

X-Ray Diffraction analysis data:

Relative clay mineral proportions:

Recorded as a percentage of total clay present, calculated according to the method described in Appendix Three.

Note: Tr = trace

P = present (proportion not determined)

Basal peak shape:

S	Sharp (well ordered clay)
M	Moderately sharp
B	Broad (poorly ordered clay)

SEM data:

Clay morphologies:

A	Authigenic clay masses identified.
D	Poorly formed or amorphous clay masses identified (detrital or early diagenetic clays?).
X	Clay not identified under SEM.

Authigenic clays were identified according to the criteria given by Wilson & Pittman (1977), which are summarised in Section 7.8.3 of this thesis. Where both authigenic and detrital masses of a clay mineral were identified in a specimen, both "A" & "D" are recorded.

Specimen (Source)		Illite	Kaolinite (Halloysite indicated by [H])	Smectite or mixed layer illite/ smectite [I/S]	Vermiculite	Chlorite	Unidentified clay masses
PA 1 (1)	XRD: SEM:	33, S A?	Tr, B D	67, S A [I/S]	- -	- -	- D
PA 4 (2)	XRD: SEM:	? A?	? ?	<100, B X	- -	- -	- -
PA 5 (2)	XRD: SEM:	<100, B X	- X	? A [I/S]	- -	- -	- D
SM 1 (4)	XRD: SEM:	27, M X	17, M A?	56, S A [I/S]	- -	? A	- -
MHQ 1 (5)	XRD: SEM:	20, M A	79, S A	1, B X	- -	- -	- -
V3 (1 2)	XRD: SEM:	4, B X	92, M D (+A?)	4, B X	- -	- -	- D
TT6 (1 3)	XRD: SEM:	52, S A	46, S X	2, M X	- -	- -	- -
Oak 1 (1 4)	XRD: SEM:	- -	100, S A	- -	- -	- -	- D
Oak 2 (1 4)	XRD: SEM:	6, M A	94, S A	- ? [I/S]	- -	- -	- -
Ross 6 (1 6)	XRD: SEM:	65, M D	35, B D	- -	- -	- -	- -
OC1 (1 9)	XRD: SEM:	P A	? X	? X	? X	? X	- D
Etna 1 (2 1)	XRD: SEM:	85, S X	11, S A	4, S X	- -	- -	- -
Etna 3 (2 2)	XRD: SEM:	83, S X	16, S A	Tr X	- -	- -	- -
Cobb 2 (2 3)	XRD: SEM:	45, M A	55, S X	[+H:Tr] [+H: A]	- -	- -	- -
Riz 1 (2 4)	XRD: SEM:	55, S X	7 D	3 X	35, S X (A?)	- -	- D
N1 (2 5)	XRD: SEM:	24, S A	61, S A	- -	15, M X	Tr? A	- -

Specimen (Source)		Illite	Kaolinite	Smectite or mixed layer illite/ smectite [I/S]	Vermiculite	Chlorite	Unidentified clay masses
L2 (27)	XRD: SEM:	55, M A	36, M D?	9, S A?	- -	Tr? A	- D
FB 1 (29)	XRD: SEM:	55, S A	45, S A	- -	- -	- -	- -
MH 1 (30)	XRD: SEM:	42, M A	58, S A (+D?)	- -	- -	- -	- -
KN 1 (31)	XRD: SEM:	P, B A	- D?	- ?	- -	- -	- D
Cam 1 (33)	XRD: SEM:	20, B A?	77, M X	3, M X	- -	- -	- -
MM 1 (34)	XRD: SEM:	87, M A?	- -	- -	13, M X	- -	- D
Cop 2 (35)	XRD: SEM:	94, M D	6, M D	- -	- -	- -	- D
Br 1 (36)	XRD: SEM:	4, B X	67, S A	- -	29, M A?	- -	- D
Con 1 (37)	XRD: SEM:	79, M A (+ D?)	21, M D?	- -	- -	- -	- D